ABSTRACT

Hallux abductovalgus (HAV) is common foot deformity that is known to predominate in women and is often assumed to be linked to the use of inappropriate footwear. The predominance of the deformity in females has been demonstrated through many surveys across different populations. The highest prevalence of the deformity reported found 44 per cent of women affect whilst the highest prevalence in men reported a prevalence of 22 per cent. Although the condition is seen less frequently in children and barefoot populations, the female foot is still affected twice as often as the male foot in such groups, weakening the theoretical association between the deformity and footwear.

A review of 100 radiographs of male and female feet found an association between the functional angle of the metatarsal head and HAV deformity and found that the female metatarsal head is more rounded than the male metatarsal head. There was no difference in the degree of metatarsus adductus (MA) deformity between males and females but in females, when the MA angle was greater than normal (24°) an abnormal HAV angle was always seen. A good association was seen between the proximal articular set angle and the HAV angle that was similar for males and females.

A three dimensional study of 100 bone-sets was undertaken using a technique not previously applied to this field of study. The bones of the medial column (talus, navicular, medial cuneiform and 1st metatarsal) were included. Several differences between in the shape of male and female foot bones were found including the more rounded metatarsal head shape in females. When the differences were considered together it was suggested that the medial column in the female foot would be more

adducted that in the male foot and the resultant adducted position of the 1st metatarsal would predispose the female foot to HAV deformity.

A study of 226 children was undertaken to investigate if a relationship between hypermobility and HAV deformity existed. A new assessment tool for measuring lower limb joint hypermobility was developed initially. No association between HAV deformity and lower limb hypermobility was found in healthy children, but a significant association was identified in children diagnosed with joint hypermobility.

In a study of foot pressure measurements in 61 children, significant differences in the amount of pressure placed through the hallux, the speed of loading of the 1st metatarsal head and the position of the centre of force through the foot were found between males and females. Associations with the pressure measurements and increasing joint flexibility were only seen for extreme levels of hypermobility. No association between HAV and plantar pressure was found.

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CHAPTER ONE BACKGROUND

Introduction

Increased female prevalence in shod and unshod populations

The aetiology of HAV deformity

Hypotheses

The aims of the thesis

1. BACKGROUND

1.1 Introduction

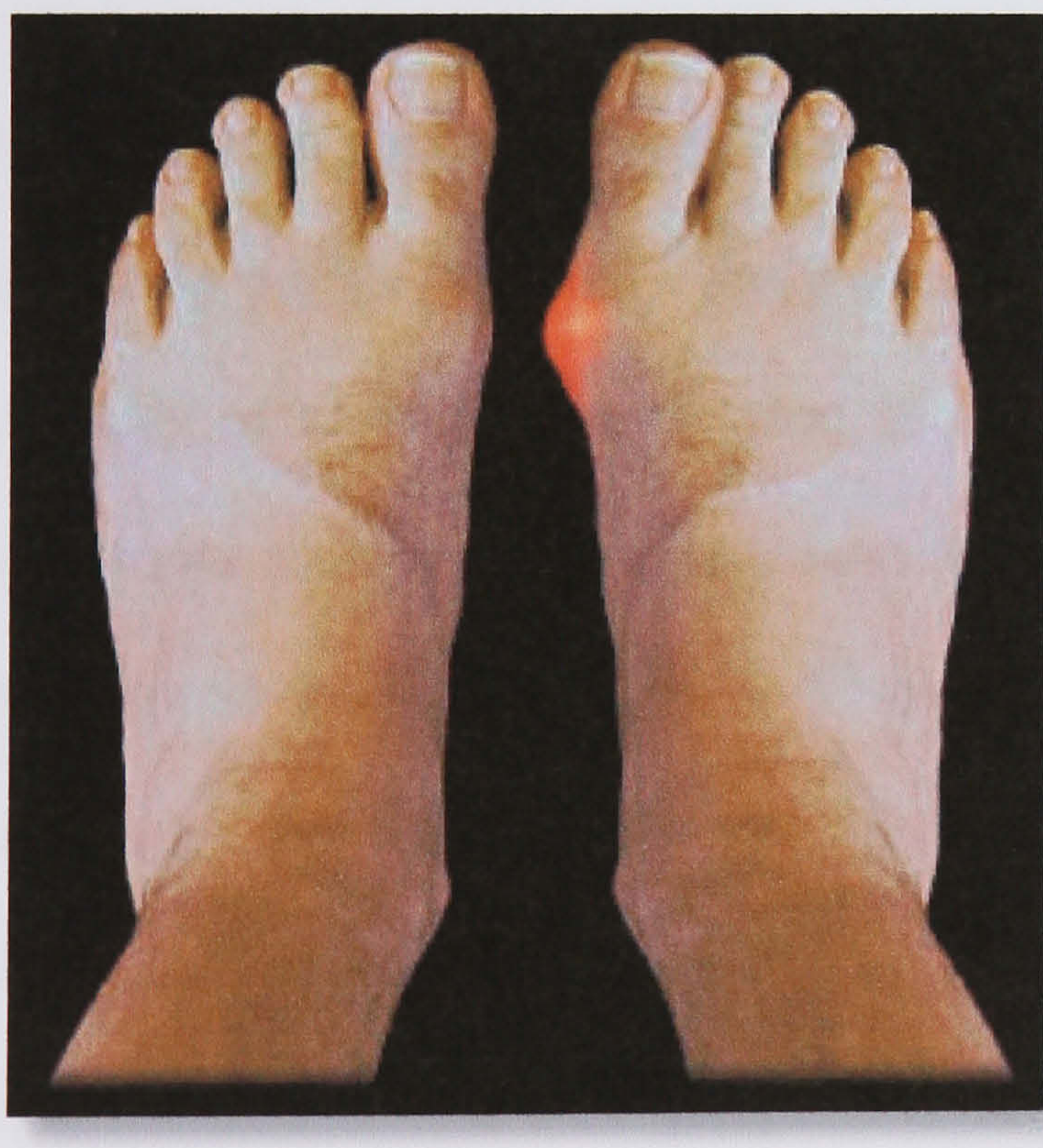
Hallux abductovalgus (HAV) is possibly the most common foot deformity and has been described as the "hallmark" of forefoot deformities (Phillips, 1994). It is recognised by prominence of the 1st metatarsophalangeal joint, created by adduction (medial deviation) of the metatarsal and abduction (lateral deviation) of the hallux which is usually accompanied by some degree of valgus rotation (see figure 1).

Figure 1. HAV deformity of both feet.

A deformity of 15 degrees or greater is popularly considered abnormal. This definition is referenced to the work of Hardy and Clapham in nearly all papers on HAV deformity (Hardy and Clapham, 1951). Hardy and Clapham measured the HA angle on X-ray in 126 control subjects (252 feet) and 89 subjects with HAV deformity. The definition for HA deformity is based on the findings of this small control group. The HA angle in the control group ranged from 0-36 degrees with a mean angle of 15.7 degrees (the morbid group had an HA angle of 12-60 degrees with a mean of 32 degrees). There was no difference in the mean HA angle between males and females in the control group. Piggott (1960) disputed this definition of "normal" finding that the metatarsophalangeal joint could remain congruent at angles of greater than 15 degrees. He considered such a definition as being arbitrary, but finally accepted its use.

The term "bunion" is more familiar to the lay population when it is used to describe a prominence of the 1st metatarsophalangeal joint that becomes painful and inflamed with bursa formation occurring as the bony prominence rubs against the upper of the footwear (see figure 2)

Figure 2. Hallux abductovalgus of the right foot with overlying, inflamed bursa.



The deformity is measured most accurately on radiographs. The hallux abductus (HA) angle (synonymous with hallux valgus (HV) angle) is the measured as the angle created between the longitudinal bisection of the first metatarsal shaft and the longitudinal bisection of the proximal phalanx (LaPorta et al.,1974). Clinical measurement can be undertaken with a goniometer. A goniometer is a protractor with extended arms that can be aligned with the parts being measured. Goniometric measurement of the metatarsophalangeal joint has been shown to be repeatable and to correlate well with radiographic measurement (Kilmartin and Wallace, 1988).

Hallux abductovalgus is a predominantly female deformity and is often assumed to be linked to the use of inappropriate footwear. The predominance of the deformity in females has been demonstrated through many surveys across different populations. The association with poor footwear is less clear.

1.2 Increased female prevalence in shod and unshod populations: What is the impact of footwear?

An interest in the prevalence of hallux abductovalgus began in the early 1900's and following this the deformity was studied in many populations world-wide. Differing methods of assessment were used in the studies, with early studies using simple techniques such as measuring around the foot and then measuring the angle formed between the medial border of the 1st metatarsal and the hallux with a protractor, or by simply grading the deformity visually. Few studies used goniometers or radiographs. Prior to Hardy and Clapham's study in 1951, the definition of "abnormal" varied between studies and thus comparison between studies is limited. Footwear was immediately recognised as having an impact on prevalence but only the earliest of studies were able to compare directly shod and unshod populations.

In 1931, Engel and Morton in the Belgium Congo and Wells in South Africa undertook studies on foot shape and described the presence of HAV deformity among the native population on the African continent, but did not provide prevalence rates (Engel and Morton, 1931;Wells, 1931). In both studies, HAV deformity was seen in the unshod population. One of the first studies specifically on HAV deformity was undertaken by Shine, a doctor working in St Helena in the South Atlantic (Shine, 1965). Measuring the HAV deformity with a goniometer, Shine compared subjects who wore shoes and those that were barefoot. Only 2% of those that were barefoot had HAV greater than 15 degrees. In the shod population, the prevalence was seen to increase with the length of time that shoes were worn so that in the elderly who had worn shoes for many years, 16% of men and 48% of women had HAV deformity greater than 15 degrees. The author noted that in this population, the footwear was of a similar style between males and females. Even when the footwear had been worn for equal lengths of time, there was always a greater prevalence for HAV deformity in females. The author suggested "*an unfavourable interaction between the female genotype and footwear must occur*" given the absence of occupational or exercise differences.

Barnicott and Hardy (1955) assessed the HA angle from footprints of barefoot Nigerians using an inked rubber mat (pedobaragraph)- a method that had been shown to correlate well with radiographic measurement. The study found that the mean HA angle was significantly less in Nigerians than Europeans, with no male to female differences being noted in the Nigerians. Although prevalence rates were not provided, the authors also found some cases of HAV deformity greater that 15 degrees in the unshod population, strengthening the idea that HAV deformity can occur in the absence of the influences of footwear.

A study by MacLennan in 1966 included 90% of the population (n=1256) of New Guinea who, at that time, were barefoot (MacLennan, 1966). Using a protractor to measure the HA angle from photographs, it was found that 2% of the population had HAV with 4% of women being affected compared to 1% of men. In males, HAV deformity, defined as being 15 degrees or greater, was seen only in age groups over 30 years old. In females, the deformity was first seen at 10 years old or greater with a peak prevalence (15%) occurring in the 40-49 year old age group. This picture of HAV deformity was seen in a survey carried out in the south of England. The condition was first seen in females age 5-14 years, when 10% had HAV deformity. The condition was first seen in boys aged 15-24 years but the prevalence did not reach 10% in males until the 25-44 year old age group (Brodie et al., 1988).

Eastern Asia has provided some of the few remaining opportunities to measure HAV in unshod or partially shod populations and compare the findings with people of the same ethnic background wearing, what was considered to be, modern footwear. A study in 1958 in China found that 33% of the shod population (n=118) compared with only 1.9% of the unshod population (n=107) had HAV deformity. The shoes worn were not constrictive but were typically a wooden clog with a single metatarsal strap or a canvas "espadrille" style shoe (Lam and Hodgson, 1958). A study in Japan compared Filipino women, who wore flip-flop style shoes (n=34) with female office workers in Tokyo who wore leather court shoes (n=40) (Kusumoto et al., 1996). There was a significant difference between the populations with the office workers having an HA angle of approximately 5 degrees greater than the Filipino women. Despite this, the mean angle in office workers was still less that 15 degrees. The authors commented that HAV deformity was seen in the unshod group but it caused no problems and was considered a "*healthy deformity*". They concluded that the increased number of patients suffering from HAV deformity since World War II was due to the effects of western style footwear. A study of an elderly in-patient population in China found that 50% of the study group had HAV deformity between 10-20 degrees when measured non-weightbearing using a protractor (Hung and Leung, 1985). In severe cases (>20 degrees), 22% of men and 19% of women were affected. This is the only study to report a greater prevalence in men over women.

In the western world, several studies have also identified an increased prevalence of HAV in women. White and Mulley (1989) found that of 96 elderly, English people living in their own home, only 6 had normal, healthy feet. Thirty percent had painful feet and 42% of the women compared with 12% of the men had HAV deformity. A similar prevalence was seen by Elton and Sanderson (1987) in their study of 297 elderly people. A larger study of Scottish geriatric in-patients (n=741) found that 48% had HAV deformity whilst a study of 459 elderly Italians found that 83% had symptomatic feet with 25.8% of women having a deformity of the hallux compared with 16.2% of men (Morris and Brask, 1980; Benvenuti et al., 1995). In the USA, a survey of 15,000 people found the prevalence of HAV deformity to be 4 times more common in females that males, occurring in up to 1 in 33 of the Caucasian population surveyed and being four times more common in black people (Gould et al., 1980). This trend towards a greater prevalence of HAV deformity in black races was not found by Gottschalk *et al* (1984) in their radiographic study. In their survey of 292 subjects, the authors found that the Caucasian group from Johannesburg had a significantly greater mean HA angle than either rural or urban dwelling black people over 10 years of age. No difference was detected in younger age groups. Like Shine, these authors also felt that the female foot was "*predisposed*" to HAV deformity in a way that was not reflected by the male foot.

Table 1 provides details and prevalence rates of the surveys identified on HAV deformity in adults.

The adult studies have tended to suggest that footwear increases the prevalence of HAV deformity in a population and this increase is greatest in females. The style or fit of the shoes worn by males and females was rarely assessed in any of the studies and it is therefore difficult to judge the appropriateness of the footwear or the contribution that it made to the deformity. Studies on children's feet have considered style and fit more frequently. Therefore information from these studies may be of value in understanding the impact of footwear on HAV deformity.

Table 1. showing prevalence rates for adult HAV deformity

Author /no.	Overall prevalence	Prevalence in females	Prevalence in males	Age / group	Defining criteria	Geographic area
Hewitt et al 1953 N=22,843			2%	17-44 yrs Army recruits		Leicester, UK
Craigmile 1953 N=358		30%	22.2%	Factory workers		
Merrill *et al* 1967 N=1011		30%	7%	Nursing home patients		USA
Gould et al 1980 N=15,000	9% (whites) 36% (others)	X4		31-60yrs		USA
	16% (whites) 32% (others)	X3.5		+61yrs		USA
Morris & Hird 1980 N=741	48%			Hospital in-patients, majority >75yrs		Scotland
Hung et al 1985 N=166		19%	22%	Hospital in-patient, 65-98yrs	Defined as >20°	Hong Kong
Elton & Sanderson 1987 N=297	34%	44%	18%	+65yrs		Manchester, UK
Brodie et al 1988 N=700		16.8%	6.8%	0-75 yrs	Defined as >15°	Wessex,UK
White and Mulley 1989 N=96	34%	31%	3%	+80 yrs		
Anwar 1989 N=135		4%		Pregnant women		
Benvenuti *et al* 1995 N=459	21%	27%	16%	+65 yrs		Italy
SUMMARY N=41806	**28.75%**	**25%**	**12 %**			

Vollans (1974) found that, except in the very young children, there was a greater prevalence of HAV deformity in girls than boys. It was found that 25% of girls and 11.6% of boys aged 16 years had HAV deformity. This compared with 27.9% of girls and 3.3% of boys aged 13 years and 1.6% of girls and 4.9% of boys aged 5 years old. Footwear was considered unsatisfactory when the shoe had high heels, pointed toes, was a slip-on, plimsoll or wellington (worn indoors) and were thus unsound anatomically and preventing normal foot function. The style of footwear worn was found to be generally unsatisfactory but this was in the older age groups, occurring after the increased prevalence of HAV deformity in girls had been seen. The style of shoe was more unsatisfactory in the girls compared with the boys in the older groups. It was found that 63.5% of girls and 39.6% of boys at 16 years old wore unsatisfactory style shoes, whilst at 13 years old, 45.8% of girls and 44.8% of boys and at 5 years old, 31.8% of girls and 31.6% of boys were wearing unsatisfactory footwear. The results of the fit of the shoes were similar to those for style but showed that girls tended to wear less well fitted footwear at all ages. This implicated the fit as a cause of HAV deformity more than the style of the shoe. The authors noted that from the age of 16 years, over two thirds of the children did not have their feet measured when buying shoes and at 13 years old, 64% of boys and 41.6% of girls did not have their feet measured. Also of note was the information that many more girls, at all ages, had poorly fitting socks or tights, compared to the boys. In this study, the HAV angle was not measured and the criteria for determining normal was not given. The criteria for defining the fit of the shoe or hosiery were not given.

Brodie (1974) found that 9.8% of boys and 21% of girls aged 8-11 years had HAV deformity greater than 10 degrees (n=439). The prevalence more than doubled for both boys and girls between the ages of 8 and 9 years compared with younger age groups. Boys tended to have less satisfactory fitted shoes (45.5%) compared to girls (33.8%). The boys shoes deteriorated in fit between the ages of 8 and 11 years whilst the fit of girls shoes remained constant. Again, approximately 25% of all children did not have their feet measured when buying shoes but this was equal for girls and boys. This study reflected an earlier study that also showed a dramatic increase in prevalence of HAV deformity at the age of 11 years old in girls, whereas the boys showed only a steady increase in cases between the ages of 4 and 15 years old (Vaines, 1967). Overall, 20% of the girls had HAV deformity compared with 9.8% of the boys, whilst 60% of the boys wore suitably fitting shoes compared to 54% of girls. In the same year a brief report from Fife on 5000 children found that 18% of children at 5 years old had HAV deformity greater than 10 degrees but by 15 years old, this had risen to 61% of girls compared to 45% of boys (unknown, 1973). Ill-fitting footwear was a greater problem in the 5 year olds, when 60% of the group were reported as having poorly fitting shoes but this reduced to 32% by 15 years old. Again, there were a greater percentage of girls than boys with poorly fitting socks and tights.

The results of a foot health survey by Cole in 1991 did not provide evidence of a link between HAV deformity and poorly fitting footwear. The survey found that 41% of boys and 41% of girls aged 9 years old, had shoes that were a different size to their feet (Cole, 1991). Twenty five percent of girls and 1% of boys wore unsuitable style shoes and 39% of boys and 5% of girls wore unsuitable hosiery. Suitability of shoes was based upon the heel height and type of fastening. Suitability of hosiery was based on the material and fit – no further descriptions were given making it hard for any reader of the study to judge how unsuitable the shoes were. The fit of a shoe was based upon the measured size of the foot and the shoe size. Despite the high reported occurrence of poor footwear, only 2 of the 114 girls (1.8%) and 1 of the 117 boys (0.86%) had early stage HAV deformity.

A study of Filipino children compared with children from Tokyo found that HAV deformity was not present in the Tokyo children (n=377) but was present in Filipino girls and boys (4.5% and 4.7%, respectively)(n=746) despite the Filipino children being generally barefoot (Kusumoto et al., 1989).

Only one study has prospectively considered the affect of good footwear on hallux position. In a group of children given carefully fitted footwear, the HA angle was measured before fitting and after one year. An improvement in the HA angle was seen after one year. At the start of the study, there were 31 cases of HAV deformity. After 6 months, this had reduced to 26 cases and reduced further to 12 cases after 1 year. The criteria for HAV deformity was not given but graphical representation of the data showed an increasing HA angle with age with children over the age of 9 years old having HAV deformity greater than 15 degrees. After 1 year of wearing good footwear, the HA angle had reduced in all age groups with no cases of HAV greater than 10 degrees being seen (Craigmile, 1953).

These studies have shown that HAV deformity is first seen at around the age of 10 years old in girls but develops a little later in boys. The style and fit of footwear is often poor in children, but the HAV deformity precedes the trend for girls to wear less satisfactory footwear than boys. This would suggest that the female foot has a predisposition to HAV deformity which may be exacerbated by the poor style and fit of footwear chosen by women. Table 2 summaries the prevalence studies undertaken in children.

Table 2. showing prevalence rates for childhood HAV deformity

<table>
<tr><th>Author
No. in survey</th><th>Overall prevalence</th><th>Infants</th><th>Primary</th><th>Seniors</th><th>Criteria for HAV</th><th>Geographical area</th></tr>
<tr><td>Craigmile 1953
N=12765</td><td></td><td>4.7% F
4.3% M</td><td></td><td>22.4% F
4..3% M</td><td></td><td></td></tr>
<tr><td>Bacon 1959
N=434</td><td>2%</td><td></td><td></td><td>4.7% (F)
0% (M)</td><td></td><td>Hampshire, UK</td></tr>
<tr><td>Greenburg et al 1963</td><td>6%</td><td>3%</td><td>6%</td><td></td><td></td><td>New York, USA</td></tr>
<tr><td>Sabbann 1965
N=1500</td><td>1.75%</td><td></td><td colspan="2"></td><td></td><td>Minnesta, USA</td></tr>
<tr><td>Vaines 1967
N=677</td><td>37%</td><td></td><td colspan="2">26% F
11% M</td><td></td><td>Yorkshire, UK</td></tr>
<tr><td>Not given
1967 N=2901</td><td>2.4%</td><td></td><td>4.2% F
0.7% M</td><td></td><td></td><td>Scotland</td></tr>
<tr><td>Denvir 1972
N=7104</td><td>24%</td><td></td><td>31.6 F
15% M</td><td></td><td></td><td>Scotland</td></tr>
<tr><td>Ivers & Gardiner 1973
N=5000</td><td></td><td></td><td>18%</td><td>61% F
45% M</td><td>Defined as >10</td><td>Scotland</td></tr>
<tr><td>Vollans 1974
N=386</td><td>12.7%</td><td></td><td>4.9% F
1.6% M</td><td>25% F
11.6% M</td><td></td><td>Cornwall, UK</td></tr>
<tr><td>Brodie 1974
N=439</td><td></td><td></td><td>21% F
9.8% M</td><td></td><td>Defined as >10</td><td>Bournemouth, UK</td></tr>
<tr><td>Gould et al 1980</td><td>0.04% (whites)
0.2% (others)</td><td></td><td colspan="2">√</td><td></td><td>USA</td></tr>
<tr><td>Enwemeka 1984 N=3144</td><td>0.84% F
0.24% M</td><td colspan="3">√</td><td></td><td>Nigeria, Africa</td></tr>
<tr><td>Kusumoto 1989
N=746</td><td>4.5% F
4.7% M</td><td></td><td colspan="2">√</td><td></td><td>Filipino</td></tr>
<tr><td>Kusumoto 1989 N=377</td><td>0%</td><td></td><td colspan="2">√</td><td></td><td>Tokyo, Japan</td></tr>
<tr><td>Cole 1990
N=230</td><td>0.8%</td><td></td><td>√</td><td></td><td></td><td>Winchester, UK</td></tr>
<tr><td>Kilmartin et al 1994 N=6000</td><td>2..5%</td><td></td><td>√</td><td></td><td>Defined as >14.5</td><td>Northampton, UK</td></tr>
<tr><td>SUMMARY
N=41313</td><td>7.66%</td><td>4.7% (F)
4.3% (M)</td><td>15.4% (F)
6.7% (M)</td><td>27.8% (F)
14.3% (M)</td><td></td><td></td></tr>
</table>

1.3 The aetiology of HAV deformity: Have differences between male and female feet been previously identified?

" The etiology of hallux valgus may include congenital, arthritis, hereditary (most common), biomechanical and trauma. The deformity usually progresses due to the biomechanics of walking. Shoes as an etiology is a myth" (Dagnall, 1994).

Shine felt that there was an underlying "*female genotype*" and Gottschalk felt that females were "*predisposed*" to HAV deformity (Shine, 1965, Gottschalk et al., 1984) but neither author made a suggestion as to the basic difference between male and female feet. A difference in external forces has been considered - the obvious difference being the force created by footwear. Other external forces may be factors associated with occupation. Molleson (2001), in a personal communication, described how the 1st metatarsophalangeal joint differed in shape between males and females in an ancient Scottish population. Molleson felt this was due to the differing roles of the sexes. Molleson felt that, in this population, the females had an expanded articular surface on the first metatarsal head to allow increased dorsiflexion of the hallux during their major occupations of grinding grain and cooking which required a squatting posture for long periods. The men, who were principally hunters, had no such change in their joint articulation (Molleson, 2001). Whether the females did squat to grind grain, or whether squatting does require greater dorsiflexion at the great toe joint is uncertain but in the modern day, no such obvious difference in occupation could account for differences in HAV formation. It would appear that HAV is a relatively new condition. A study on the etiology of hallux valgus in Japan reported that footprints dated to the Johmon period (6000-500BC) showed no evidence of HAV deformity (Kato and Walanabe, 1981). This may be because HAV did not exist at this time or because there were insufficient footprints to show a deformity that may not have been very common. These authors found the earliest reference to the deformity in medical texts was from a French physician in the 18th century. Another author suggested that there is no representation of hallux valgus in Greek and Roman statues (Phillips, 1994) so it was unlikely to be a common deformity. It is uncertain whether the sculptors would have depicted such a blemish in their idols had they have been present.

A picture by Raphael painted in the early 16th century has been said to show HAV deformity (see figure 3). Since artists of those times rarely completed a commission single-handedly, it could be proposed that a student painted the foot and failed to reach the perfection of Raphael. Given that the figure's opposite foot (left) appears to have a high arch and an over-sized, triggered hallux, it would be unlikely that the right foot would have an HAV deformity. Unless the artist was aiming to depict as many foot deformities as possible in one painting, it is hard to accept that the figure has HAV deformity and so the time at which this forefoot deformity became prevalent remains unclear.

Figure 3. Coronation of the Virgin by Raphael.

Image removed due to third party copyright

In 1997, Spooner looked at several factors believed to be related to HAV deformity from a genetic / inheritance view point, having recognised that 47% of textbooks on hallux valgus cited inheritance as an aetiological factor, without scientific support (Spooner, 1997). The other aetiological factors listed in textbooks were footwear (65%), metatarsus primus varus (56%), pronation (35%), 1st metatarsal length (21%), equinus (13%), metatarsal head shape (9%) and other factors such as first ray position, neuromuscular disease, previous surgery, body weight, age, atavistic regression and leg shape were reported less frequently. The metatarsus primus varus position occurs when the first metatarsal is adducted towards the midline of the body and may be due to the shape of the facet on the medial cuneiform or occur during function due to the position of the 1st ray axis of movement (Phillips, 1994). Metatarsus primus varus (MPV) was originally thought to occur after the development of HAV deformity, with the change in position of the hallux creating an adductory force against the metatarsal head (Hardy and Clapham, 1951). However, more recent study has suggested that MPV precedes HAV deformity (Kilmartin and Wallace, 1994) and it is the changing position of the metatarsal that results in a muscle imbalance around the joint. The adductor hallucis muscle and long flexor and extensor attaching to the hallux gain a mechanical advantage resulting in a pull on the proximal phalanx into abduction.

Spooner (1997) summarised the research to date that has considered inheritance of the deformity and suggested that the evidence appeared strong but care should be taken as there would be a shared environment within families and the methods of obtaining a family history were weak, often relying on recall only.

Spooner considered the degree of abnormal subtalar joint pronation, 1^{st} metatarsal protrusion, 1^{st} ray position and metatarsal and digital formulae. The influence of genetics was found in all areas, but these were inflated by the shared environments between parents and children. For HA angle, there was little difference between the magnitude of the genetic components for males and females but strong differences in environmental influences (for example, footwear) did exist between the genders. The author felt that foot proportions and anatomical differences between males and females would not account for the increased female prevalence and suggested that the genetic link to ligament laxity in females, may account for the differences seen. With ligament laxity, the 1^{st} metatarsophalangeal joint and 1^{st} metatarsocuneiform joints are more likely to be unstable and therefore more easily affected by environmental factors such as poor footwear (Spooner, 1997). The study did not measure ligament laxity.

Only two studies were identified that had looked at anatomical differences between male and female feet. In a study on the size and angle of pull of the adductor hallucis muscle, no significant differences were reported between the sexes, after correction was made for foot size. In one study on the shape of the metatarsal head in relation to HAV deformity no difference was found in the shape of joint surfaces between males and females (Gutierrez Carbonell et al., 1998).

1.4 Hypotheses

Hallux abductovalgus is a forefoot deformity that predominantly affects the female foot. Few studies to date have investigated whether the male and female foot differ in structure. This study hypothesises that the morphology of the female foot is different to the male foot. A difference in the size of the foot bones and shape of the articular facets would indicate that the feet are structurally different and may therefore function differently. The shape of the joint surfaces of the bones of the medial column of the foot may lead to a greater degree of adduction of the 1st metatarsal (metatarsus primus varus) in the female which predisposes to the development of hallux abductovalgus deformity. This has been described as atavistic regression – where the foot position is returning to a previous stage in evolution. The study hypothesises that the female foot has developed slower than the male foot and thus has some remnants of the earlier grasping hallux, unlike the male foot. It is known that females are more flexible than males. The study hypothesises that the hypermobility will be reflected in the lower limb and foot of females, demonstrating greater flexibility than males. This increased flexibility will exacerbate an underlying preponderance to HAV deformity such that an association will be seen with increasing flexibility and increased HAV deformity. Hypermobility in the lower limb and foot will influence the pressure patterns under the foot such that overloading of the 1st metatarsophalangeal joint will occur and lead to the development of HAV deformity.

1.5 Aims of Study

1. To determine if a difference existed between male and female metatarsals measured on radiographs.

By studying radiographs, differences in the shape of the first metatarsal between males and females were investigated. The study was used to determine if important measurements were identifiable for use in the next stage of the study. Radiographs were digitised and measured using computer software for greater accuracy. This technique has not been used previously in this field of study.

2. To determine if a difference in structural and functional measurements existed between male and female foot bones.

Using the bone collections held at the Natural History Museum, the bones of the medial column of the foot were studied to determine if there was a difference in the size of the bones and the shape of the articular facets. A novel method for measuring bones in three dimensions was used. Any differences were compared to the causes of HAV deformity described in the literature.

3. To compare flexibility of the ligaments in the lower limb and foot between the sexes.

A group of children were used to measure the joint movement in the lower limb and foot and therefore provide information regarding differences in soft tissue elasticity between the sexes. A new scoring system was developed and piloted and compared to the "gold standard" measuring system in current use. The flexibility score was compared between males and females and correlated with the degree of HAV deformity present.

4. To compare the peak pressures placed through the hallux and 1st metatarsal head in males and females in males and females.

Functional difference in males and female feet may be identified through the investigation of foot pressure measurements. The pressure measurements and the pressure distribution under the foot was considered with reference to the influence of increasing joint flexibility, 1^{st} ray position and HA angle.

Such a study, comparing the force and flexibility in the medial column, has not been previously undertaken in children.

5. To consider if any of the present treatments for HAV deformity address the possible etiological factors found in this study, as well as other aetiologies that are discussed in the literature.

A systematic review was undertaken to search for evidence on the efficacy of HAV treatments. The treatments identified were compared to the earlier findings of the study.

CHAPTER 2 MALE AND FEMALE BONE SHAPE: A RADIOGRAPHIC STUDY OF THE FOREFOOT

2. MALE AND FEMALE BONE SHAPE: A RADIOGRAPHIC STUDY OF THE FOREFOOT

2.1 Introduction

There are many radiographic studies that have considered the bony position in relation to hallux abductovalgus deformity both in the rearfoot and in the forefoot. In the forefoot, the shape of the metatarsal head, metatarsal length, the proximal articular set angle, intermetatarsal angle and metatarsus adductus angle have received the most attention and are thought to be strongly related to the development of HAV deformity, but few studies have addressed these conditions with reference to the increased prevalence of HAV in the female foot. Differences between the shapes of male and female bones have rarely been addressed.

2.11 Metatarsal head shape

The stability of any joint is dependent on the shape of the joint surfaces and the strength of the supporting ligamentous structures and related muscles and the force to which the joint is subjected. The shape of the metatarsal head has been cited as a factor in the development of hallux abductovalgus (HAV) (Coughlin and Mann, 1987; LaPorta et al., 1974; Morton, 1935; Phillips, 1994). The shape has been classified into three general forms: round, flat or chevron (Coughlin and Mann, 1987; LaPorta et al., 1974) (see figure 4) but the actual curvature has rarely been measured. Excessive curvature of the 1st metatarsal head is believed to lead to instability allowing the proximal phalanx to drift laterally causing deformity at the metatarsophalangeal joint, whereas a flat or chevron type metatarsal head is thought to be more stable (Coughlin and Mann, 1987; LaPorta et al., 1974). This hypothesis remains untested by substantial data and differences between male and female metatarsal head shapes has rarely been considered.

Figure 4. Radiographs showing a round (A), flat (B) and chevron type (C) metatarsal head.

A B C

Four studies have been undertaken to evaluate the relationship between the metatarsal head shape and HAV deformity (Brahm, 1988; Fellner and Milsom, 1995; Gutierrez Carbonell et al., 1998; Kilmartin and Wallace, 1991). Differences between male and female bone shape were studied in only one trial (Gutierrez Carbonell et al., 1998) despite the increased prevalence of hallux abductovalgus in females (Benvenuti et al., 1995; Gould et al., 1980; Kilmartin et al., 1994).

In 1988, Brahm undertook a retrospective study of 19 weightbearing radiographs (13 patients). Using silhouettes taken from the films, the radius of the curvature of the articular surface was calculated by locating the edges of the joint surface, joining these two points and then dropping a perpendicular at the mid-point of this line. The intersection of the dome of the metatarsal head created a third point through which a "best-fit" curve could be drawn with a pair of compasses and the radius measured with a ruler (see figure 5).

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Figure 5. Calculations made by Brahm (1988) for metatarsal head width and radius.

The width of the metatarsal head was divided by the radius. The author claimed that the use of the width/radius value would eliminate differences in magnification effects of the X-rays. This fact is not proven. It is also unclear as to what the figure of width/radius expresses. If the radius of curve stays the same between two bones, but the width is greater in one bone then the value of width/radius is greater in the wider bone, despite having the same radius. The smaller bone will appear flatter but also has less articular surface so theoretically, the hallux would not deform so much (see figure 6)

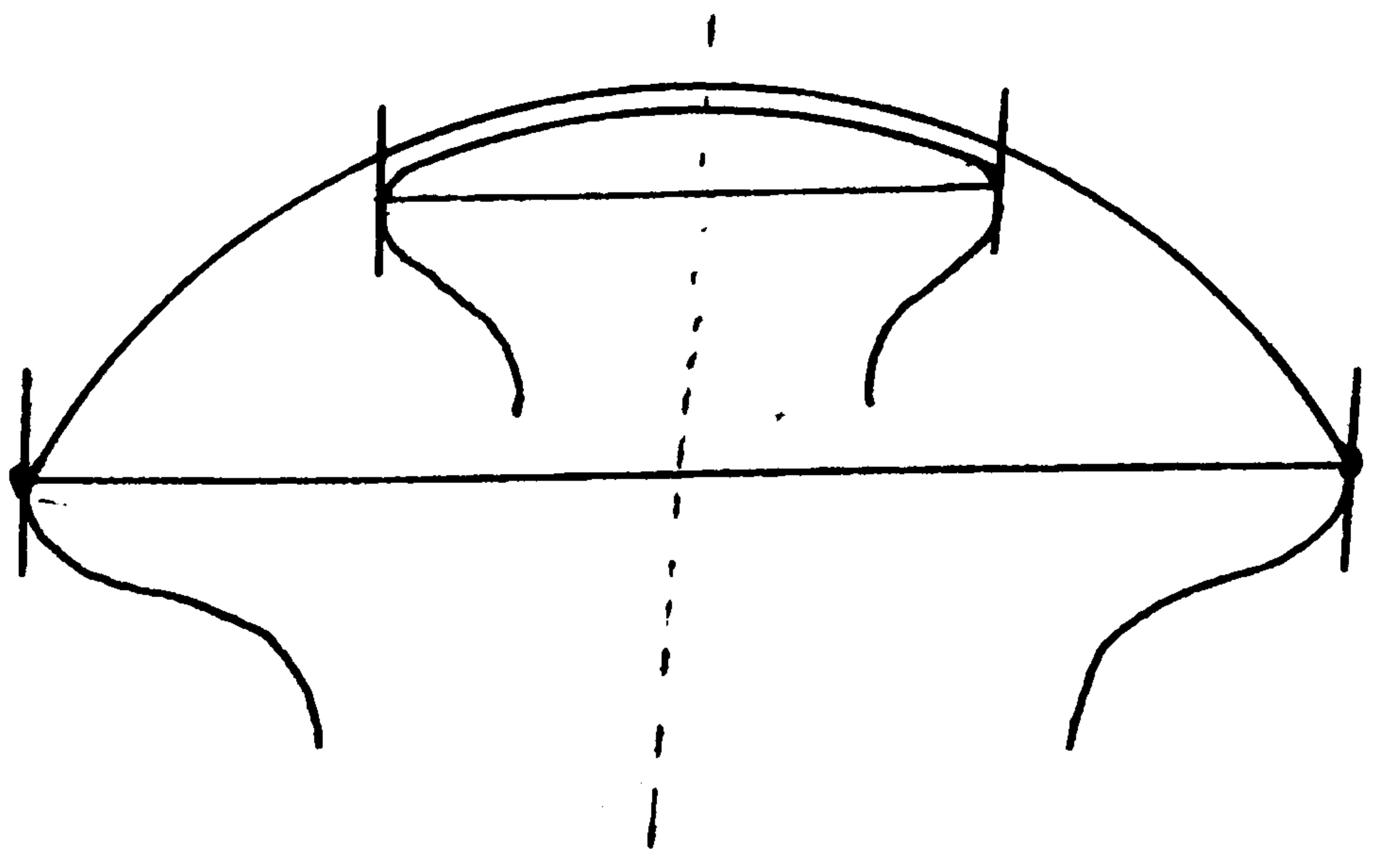

Figure 6 showing two bones with the same radius of curve, but different widths. (The smaller bone appears flatter and has less articular surface).

Two bones of the same width may have different curvatures. If the radius is smaller, the width/radius value increases. The bone with the smaller radius appears more curved, but also has a greater amount of articular surface. However, when two bones are considered, one with twice the width of the other, the other with half the radius, the width/radius value will be the same. In this situation the bones had the same curvature of joint surface but one is proportionally smaller in size. It can therefore be seen that the figure of width/radius is reflecting the shape of the joint surface.

Using this ratio, Brahm found a Pearson r correlation of $r = 0.57$ ($p<0.05$) between the ratio and the HAV angle. The higher ratios (indicative of a more curved metatarsal head) were seen with a greater severity of HAV deformity. The author discussed the possibility that the metatarsal head may have been remodelled secondary to the HAV deformity occurring so that a rounded head was the result rather than a cause of HAV deformity. It is known that a rounded metatarsal head may become flattened in some pathological processes such as Freiburg's disease of the 2nd metatarsal head, but it is not known whether the mechanical forces associated with HAV deformity may make an initially flat bone become more rounded. Brahm noted a lack of destructive changes to the bone on X-ray and thereby concluded that the metatarsal had not been remodelled.

Kilmartin and Wallace (1991) studied 50 radiographs of 100 feet with juvenile HAV. The children were placed in their natural angle and base of gait for the weightbearing X-rays. The shape of the metatarsal head was determined by firstly bisecting the metatarsal shaft longitudinally. A second line was placed tangentially across the metatarsal head curvature that was perpendicular to the bisection line. The length of the tangential line in contact with the articular surface was measured. It was proposed that a square metatarsal would have a longer length of articular surface in contact with the tangent than a rounded metatarsal.

This method only works if the metatarsal heads are of the same size. If two bones have the same curvature but one is smaller than the other the amount of tangential line in contact with the articular surface is also smaller. Therefore the smaller metatarsal head (which looks flatter) would be classified as a rounder metatarsal by this method (see figure 7). In the particular study, all children were of the same age and therefore may have had similar sized metatarsal heads allowing the calculation to work. However, it is possible that the sizes were different in this age group.

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A B

Figure 7 showing the method of Kilmartin and Wallace (1991) a). with a small metatarsal head having less contact with the tangential line despite having the same degree of curvature as the larger metatarsal head and b). how the more curved metatarsal head might also have less contact with the tangential line than a flatter metatarsal head.

The authors found no relationship between the shape of the metatarsal and HAV deformity ($r = -0.294$, $r^2 = 0.08$) and concluded that the shape of the metatarsal head contributed little to HAV deformity.

Fellner and Milstrom (1995) used 50 radiographs with HAV deformity and 30 age and sex matched control radiographs in order to compare the two previous methods of Brahm (1988) and Kilmartin and Wallace (1991). Using the method from Brahm, a significant difference was found between the HAV and control group ($p < 0.001$) with the HAV group having a value indicative of a more curved metatarsal head. The Pearson r correlation found was much less than in the original study ($r = 0.387$). Using the method from Kilmartin and Wallace, no significant difference between the groups was detected. The authors comment that they, as well as Brahm and

Kilmartin, looked for a linear relationship when a stronger correlation may be found with other models of analysis. Indeed, if the surface of the metatarsal head is considered, the curvature can only reach a maximum of 180 degrees and then the hallux valgus will reach a maximum angle. Therefore a logarithmic regression model may be more appropriate to apply.

In the most recent study, the shape of the 147 metatarsal heads (73 feet) were classified through observation into flat, round and chevron groups and were compared to the HAV deformity.(Gutierrez Carbonell et al., 1998) The round metatarsal head shape predominated and was significantly related to the HAV angle ($p = 0.04$). Correlation coefficients were not given in the data. The authors looked at many different features associated with HAV and found that in these and in the metatarsal head shape, there was no difference between males and females.

None of these studies considered the length of the articular surface which may also play a role in the development of HAV. Given the same degree of curvature, if the joint surface is longer, the phalanx would have to displace further than on a short articular surface. Latimer and Lovejoy (1989) made this point. These authors found that female gorillas have greater range of movement in their joints than male gorillas, due to having rounder joint surfaces despite having smaller sized joints. They stressed the need to account for joint size when interpreting function. The authors recommended the use of the functional angle, which can be calculated from the chord length and the radius of the curved surface:

Functional angle of curve $= 2\sin^{-1} \frac{\text{Chord length}}{2 \text{ Radius of curve}}$

This is similar to the measurement of Brahm who used width (chord length) / radius. The calculation above is more sophisticated, using trigonometry to calculate the angle through which the joint surface allows movement (see figure 8).

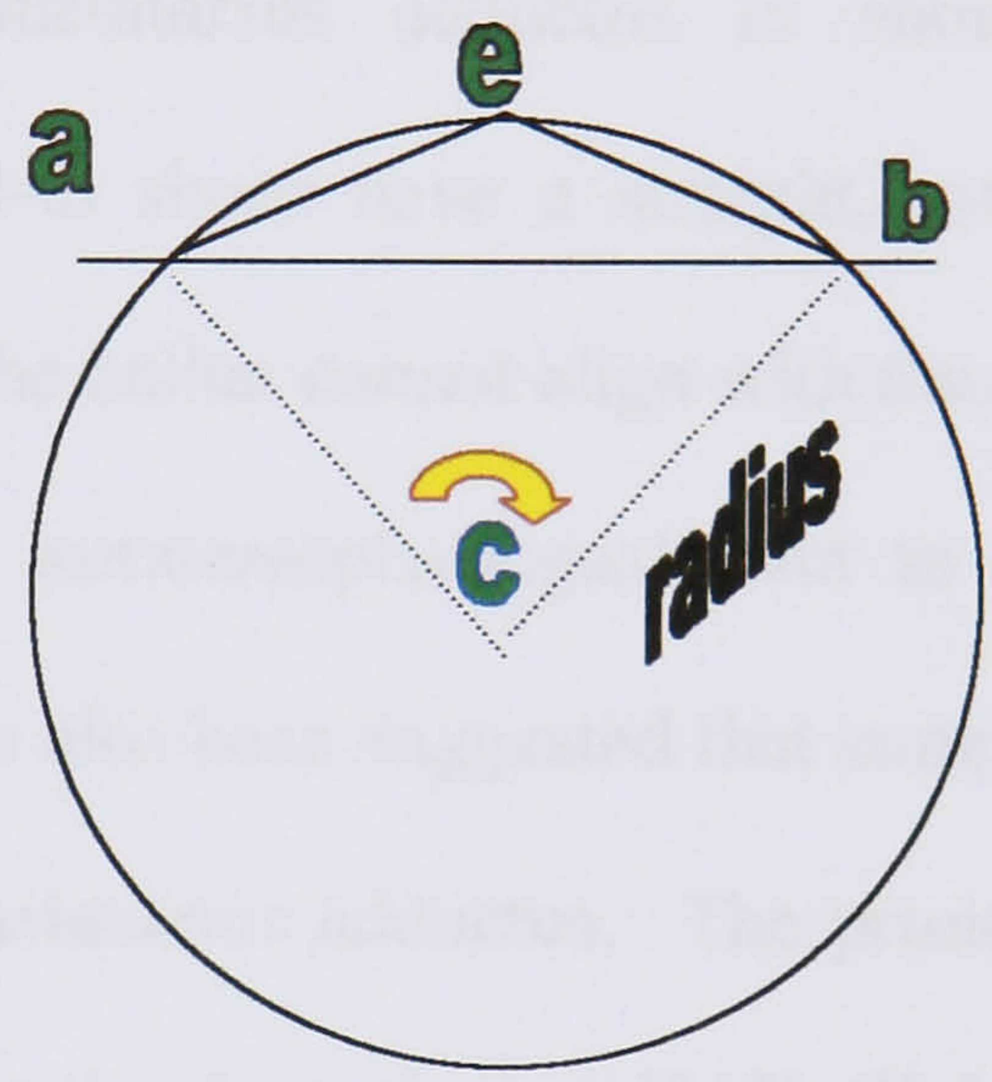


Figure 8. Calculating functional angle (c) using the chord length (ab) and the radius., whereby functional angle = 2x sin (½ab/r).

2.12 The metatarsus adductus angle

Metatarsus adductus (MA) has been cited as a cause of hallux abductovalgus, particularly in the juvenile foot (Coughlin and Mann, 1987; Tax, 1980) and it has been suggested that unrecognised MA deformity is a cause of recurrence of HAV deformity following surgery (Pontious et al., 1994).

Metatarsus adductus is described as a structural deformity occurring at the LisFranc joint (metatarsotarsal joints) with the metatarsals being medially deviated with reference to the lesser tarsus (Rothbart, 1972; La Reaux and Lee, 1987). It would not be unexpected to find hallux abductovalgus associated with metatarsus adductus given that HAV is related to a medially deviated 1st metatarsal (McCrea and Lichty, 1979; Houghton and Dickson, 1979; Hardy and Clapham, 1953) as seen by an increased intermetatarsal angle (IM) on X-ray. Piggott (1960) was concerned that not all cases of HAV had an increased IM angle. Metatarsus adductus would account for such cases since when all the metatarsals are adducted, the IM angle remains small.

HAV deformity has been linked with metatarsus adductus in shoe-wearing populations (Rothbart, 1972). Most closed-in shoes have a straight, rounded or pointed toe-box. When wearing such shoes, the hallux cannot align with the adducted 1st metatarsal but is forced laterally at the metatarsophalangeal joint to a degree dependant on the shape of the toe-box. It has also been suggested that compensatory pronation occurs to abduct the forefoot in metatarsus adductus. The pronation and subsequent forefoot instability is involved in the formation of HAV (Kelso et al., 1982; Mahan and Jacko, 1991; Banks et al., 1994; Trepal, 1989).

Metatarsus adductus is said to occur in 3 per 1000 live births, with an equal distribution between males and females (La Reaux and Lee, 1987). The condition is more common if another family member is affected. The metatarsal position is exaggerated in the fetal foot and with an angle of 50 degrees adduction of the first metatarsal being seen. Radiological evaluation of the metatarsus adductus angle is classically obtained by taking the angular measurement formed between the line bisecting the 2nd metatarsal and the longitudinal line bisection of the lesser tarsus, on standard weightbearing X-rays. This angle measures between 22-25 degrees at birth but reduces by adulthood. The normal adult value is between 5-20 degrees and is considered pathological above 21 degrees (Rothbart, 1972; La Reaux and Lee, 1987;

Oster, 1994). A simplified method which measures the angle between the 2nd metatarsal bisection and the 2nd cuneiform bisection, has been shown to be valid and has been used in several trials to examine the relationship between metatarsus adductus and HAV (Engel et al., 1983). The simplified method gives values that are 3 degrees greater than the traditional method so that with this approach, angles greater than 24 degrees are considered abnormal in an adult.

The relationship between metatarsus adductus and hallux abductovalgus was first investigated in 1987 (La Reaux and Lee, 1987). Four hundred and sixty adult, weightbearing X-rays were examined. The cohort was divided into two groups: the study group had hallux abductovalgus ($>15^0$), the control group had no HAV. There were 230 radiographs in each group. The control group had a 13% prevalence of metatarsus adductus with the mean MA angle being 19 degrees. The HAV group had a prevalence of 35% - a significant difference ($p<0.001$). The mean metatarsus adductus angle in the HAV group was only 3.7 degrees greater than the control group. No correlation analyses were carried out on the data. Differences between males and females were not assessed.

Griffiths and Palladino (1992) measured 115 radiographs although it is unclear whether they used the simplified or traditional method. No patient had clinical signs or symptoms related to hallux valgus. Hallux abductovalgus deformity was positively associated with metatarsus adductus deformity when tested with regression analysis ($p<0.001$). Despite this significant correlation, the regression coefficient was low ($R=0.35$, $R^2=0.13$). The authors divided their cohort into degrees of severity of metatarsus adductus and also into two groups consisting of the presence or absence of metatarsus adductus. Although there was a significant difference in HAV deformity in the group with metatarsus adductus compared to the group with no metatarsus adductus, there was considerable overlap in HAV deformity when compared with the severity of metatarsus adductus. A threshold of 15 degrees of metatarsus adductus was suggested for the development of HAV despite this being within the normal range of metatarsus adductus angle ($10\text{-}20^0$). Even in the group with severe metatarsus adductus (21-25 degs) the HAV angle remained normal (14.8 degs). The study also considered whether males and females had different degrees of deformity. No sex difference was found for metatarsus adductus angles or HAV angles.

Banks *et al* (1994) undertook a study of 40 adolescents and children presenting for HAV surgery (72 feet). This prospective study aimed to determine if a correlation existed between metatarsus adductus and HAV deformity. A significant correlation between HAV and metatarsus adductus was found ($p=0.009$) but again the correlation coefficient was very low ($R^2 = 0.1$). *A posteriori* analysis was carried out after the initial regression analysis. A least squares regression model was applied in the data which increased the regression coefficient to $R^2 = 0.48$. Further analysis was carried out as the authors sought non-linear models. Since the MA and HAV angles would be limited in their upper values, a logarthmic model would seem likely. A threshold value of 14 degrees of metatarsus adductus was suggested since a stronger linear relationship was found between HAV and metatarsus adductus greater than 14 degrees. This concurred with the study by Griffiths and Palladino (1992). The authors developed a complex curve equation that linked several features to HAV deformity but did not repeat the analysis prospectively.

In their study of metatarsus adductus in patients having HAV surgery, Pontious *et al* (1994) examined pre-operative 65 X-rays and considered metatarsus adductus angles of greater than 24 degrees as abnormal. A total of 75.4% of patients had an abnormal metatarsus adductus angle with a mean MA angle of 27 degrees. This was twice the prevalence found by Banks *et al* and the authors stated that it was their contention "*that unrecognised metatarsus adductus is one factor that heavily contributes to the high recurrence in adolescent and adolescent-onset hallux abductovalgus*".

None of these studies used radiographs of the foot in a subtalar joint neutral position with the midtarsal joint fully pronated. The presence of subtalar joint pronation would be expected to decrease the metatarsus adductus angle whilst inversion of the forefoot would increase the metatarsus adductus angle. Failure to align the foot in a neutral position for the radiograph may therefore obscure the true prevalence of the condition. However, it would be particularly difficult to maintain such a position to the same degree in all patients for weightbearing X-rays and so the resultant error perhaps has to be accepted.

2.13 The Proximal Articular Set Angle

The Proximal Articular Set Angle (PASA) is described as "*the angle formed between a line representing the effective articular surface of the first metatarsal head and a perpendicular to a line representing the bisection of the shaft of the first metatarsal*" (LaPorta et al., 1974) (see figure 9).

Figure 9 showing the line representing the effective articular surface and metatarsal bisection.

LaPorta *et al* (1974) describes the relationship between hallux abductovalgus (HAV) and the PASA stating that in the normal adult foot, the PASA is an angle of 0–8 degrees and is tilted laterally to account for the 0-8 degrees adduction of the first metatarsal. It is unclear from their paper the source of the normal range of angles quoted or whether the relationship between the angles has been tested.

Other authors have measured the angle in adult feet. In one study of 41 female radiographs, the PASA was found to have a range of 0-15 degrees (Steel, 1980). Another study found a mean PASA of 6 degrees (range -3 – 26 degrees) in 100 cadavers (Richardson et al., 1993).

The reliability of the measurement of the PASA has been frequently studied. The radiographic measurement of the PASA has been found to differ in value from the intra-operative measurement (Evans and Lile, 2000; Amarnek et al., 1986) although a significant positive correlation existed between the measurements ($r = 0.6$, $p < 0.05$). A difference between the radiographic and intra-operative measurement is unsurprising since the radiograph does not show the sagittal plane deviation of the metatarsal and phalanx and therefore the curve of the metatarsal seen may represent the curve across any part of the metatarsal head. For example, if the metatarsal is in a plantarflexed position, the dorsal edge of the metatarsal head will be seen in the anterior-posterior radiograph. If the metatarsal is dorsiflexed, the curve across the central area or plantar edge of the head will be seen. When measuring the curve intra-operatively, the observer can take the reading at any chosen point but it will not necessarily correspond to the same point on the radiograph. It has been found that the sagittal plane deviation does not influence the radiographic findings as much as the varus or valgus rotation of the metatarsal (Vittetoe et al., 1994). In a cadaver study, it was found that the normal method of measuring radiographs was not sensitive to the rotation of the metatarsal although the radiographic method did have a 95% probability of being within 5 degrees of the true measurement (Vittetoe et al., 1994). When measuring intra-operatively, the observer can identify the medial and lateral borders of the bone and therefore measure the true transverse curvature. On radiographs, the medial and lateral borders may be incorrectly identified as the rotation of the bone is difficult to assess and therefore the curvature measured will be different. One study has reported that the typical method of measuring the PASA is accurate to within 5 degrees, when compared with a method adding metal beads to aid identification of the medial and lateral edges of the articular surface on X-rays (Richardson et al., 1993).

The intra- and inter-observer reproducibility of the measurements has been tested with varying results. There would appear to be difficulty in establishing which part of the joint surface represents the "effective" articular surface for some observers but not for others (Griffiths and Palladino, 1992). There is particular difficulty in measuring an articular surface on radiographs since these only show bone rather than articular cartilage. Vittetoe *et al* found that the differences in identifying the articular surface led to good intra-observer reliability but poor inter-observer results. In one of the largest inter-observer tests, 300 practitioners measured a single X-ray (Fox and Firstein, 1989). A wide variation in measuring capabilities was reported but unfortunately the data was not analysed in such a way as to test a specific hypothesis or describe the significance of the results; only trends in the results were considered.

Despite the considerable work undertaken to test the reliability of the measurement technique, the relationship between the PASA and HA angle appears not to have been studied well. Pontious *et al* (1994) commented that the PASA has significant importance in the correction of adolescent-type HAV deformity but did not provide any convincing data. Griffiths and Palladino (1992), in their study of 115 feet found that the PASA increased as the metatarsus adductus angle increased, which had already been noted by an earlier study, but the relationship between the PASA and HAV angle was not tested.

2.2 Aim

It is questionable whether any of the trials on the metatarsal head shape measured the curvature of the metatarsal head with adequate consideration of bone size. This trial used the functional angle suggested by Latimer and Lovejoy to investigate the relationship between the roundness of the metatarsal head compared to the HAV angle. The HAV angle was also be compared to the metatarsus adductus angle in healthy patients. The study differed from previous studies by including adults, without pre-selecting hallux valgus deformity and considering equal numbers of male and female patients. The relationship between HAV angle and the proximal articular set angle was studied to clarify the relationship. Since the prevalence of HAV deformity is greater in females, the differences between male and female bone shape and positions was examined for all relationships.

A novel method for measuring radiographs has been introduced.

2.3 Method

Sample

One hundred radiographs (50 male and 50 female) were selected from the collection held at the London Foot Hospital. All radiographs were taken at the Royal National Orthopaedic Hospital and were taken by different radiographers. However, a standard procedure is used at that hospital with the X-ray beam directed 15 degrees to the navicular, 100cm from the foot. All views were weightbearing, taken in the dorsal-plantar plane (A-P).

Radiographs of patients were included when there was a clear view of the metatarsophalangeal joint articular surfaces. Only radiographs of patients under 40 years of age were used in order to reduce the likelihood of osteoarthritic changes. Patients were in good general health and did not have a medical history of joint disease such as rheumatoid arthritis, osteoarthritis or diabetes (Charcot arthropathy). No previous surgery on the 1st ray had been undertaken. Only radiographs were selected that had been taken for reasons other than investigation of the 1st metatarsophalangeal joint area.

Patients with and without HAV were included in order to evaluate the metatarsal head variables across the range of metatarsophalangeal joint angles. It was not possible to control for foot type (pronated / cavoid).

Table 3 provides a summary of exclusion criteria.

Table 3. Summary of exclusion criteria

Obvious degeneration or unclear articular surfaces at the 1st mtpj
Over 40 years old
Non-weightbearing view
History of trauma to the 1st mtpj
Potential for unrecognised trauma to the 1st mtpj (neuropathy)
Radiographs taken for investigation of 1st mtpj
Joint disease affecting the mtpj (rheumatoid / osteo / Charcot arthritis)
Previous surgery to the medial column of the foot

Each radiograph was digitised using a suitable camera. A standard procedure was used in order to reduce the effect of the placement of the camera on the digitised image of the radiograph with the camera mounted on a tripod at a fixed distance (32cm) from the x-ray viewer. A spirit level was used to ensure that the camera was not tilted between radiographs. A small torch was fixed to the camera and for each picture the light beam was centred on the metatarsal head. The camera was used at its minimum zoom position and the picture taken with remote control to prevent movement of the camera.

The OSIRIS software package was used to analyse the x-rays (Osiris, 2003). In order to test the accuracy of the software initially, 20 radiographs were digitised. A ruler was included in each of these pilot images to provide a check against parallax with five 1cm distances being measured down the ruler to ensure that the distances stayed constant.

The image was enlarged to 200% for maximum visibility.

To measure the functional angle of the metatarsal head, the chord length was measured from the edges of the articular facet and a "best fit" curve applied to the metatarsal head (see figure 10).

Figure 10. Digitised image of radiograph with chord length and best-fit curve applied.

The functional angle was found by trigonometry (see figure 11).

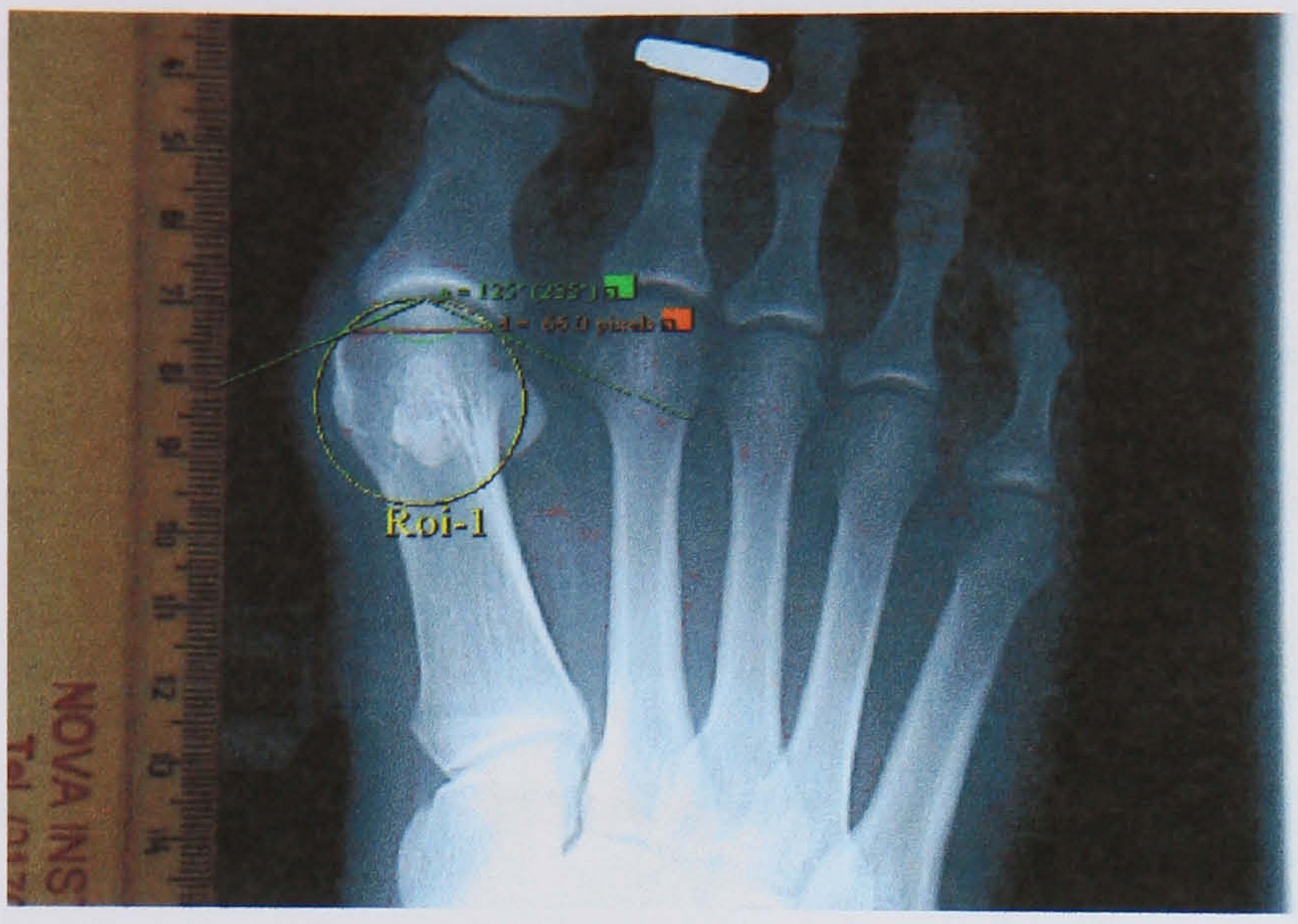


Figure 11. Calculating the angle of curve of the metatarsal head.

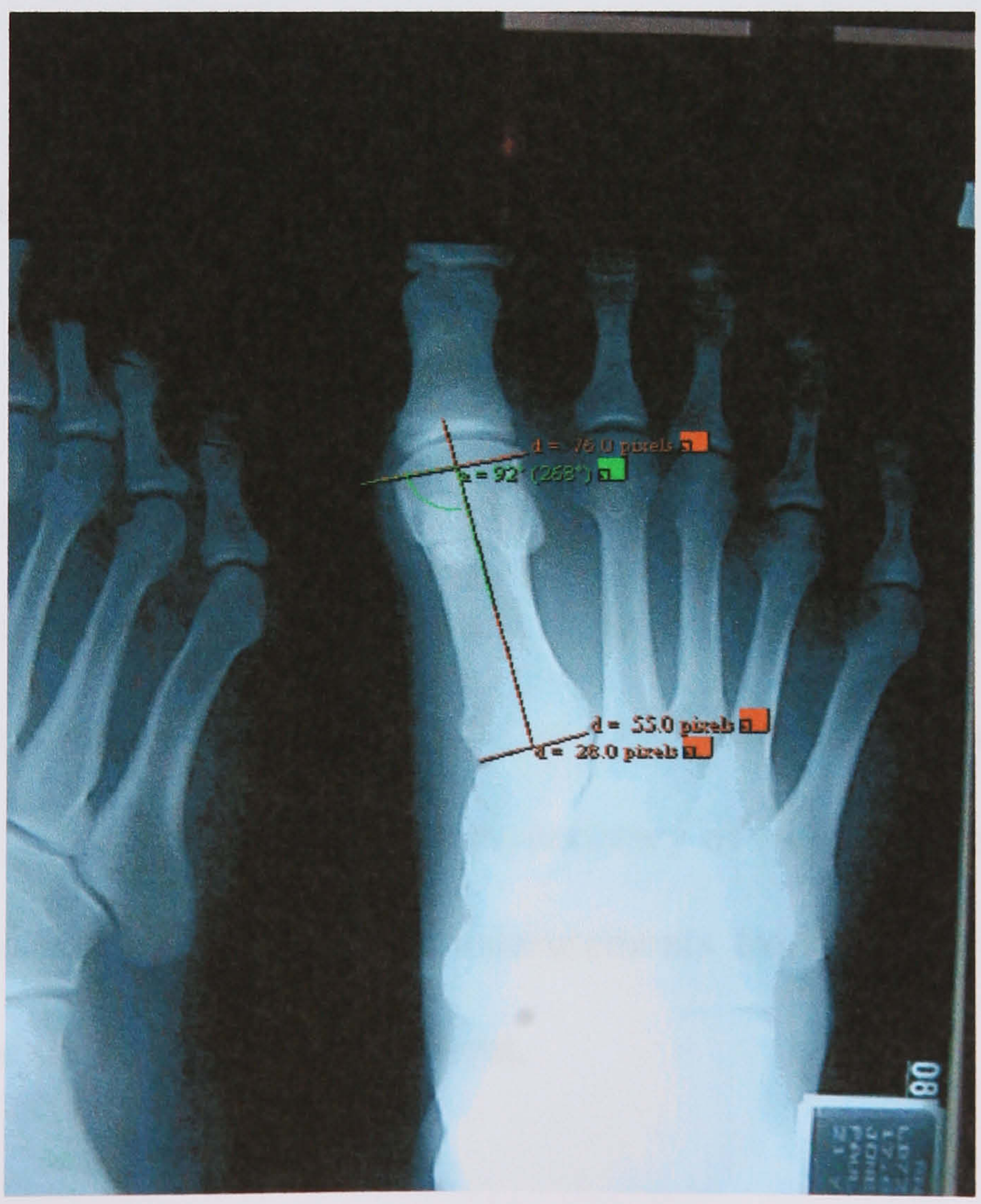
The metatarsus adductus angle was measured using the method suggested by Engel *et al* (1983). The angle between the line bisecting the 2nd cuneiform and 2nd metatarsal was calculated (see figure 12).

Figure 12. showing the method for measuring the metatarsus adductus angle.

The proximal articular set angle was measured using the method described by LaPorta *et al* (1974). On the digitised image, a line was drawn from the medial to lateral side of the articular surface of the metatarsal head establishing the limits of the "effective articular surfaces". A second line was drawn from the medial to lateral side of the base of the metatarsal. The centre of this line was found and was used to anchor a line-bisection that was placed along the shaft of the metatarsal (see figure 13). The shaft of the proximal phalanx was also bisected.

The angle between the articular surface and metatarsal bisection line was calculated to give the PASA.

Figure 13. Digitised image of a radiograph with line bisection of the metatarsal shaft and a line across the medial and lateral edges of the articular surface of the metatarsal head creating the PASA (92°-90°=2° PASA).



The hallux abductus angle was found by identifying the longitudinal bisection lines of the metatarsal and proximal phalanx. The distance between the medial and lateral edges of the base and head of each bone was found. The midpoints calculated and the midpoints joined to form the bisection (see figure 14).

Figure 14. Showing HA angle

All measurements were taken 5 times by a single observer on separate days with the mean of the five measurements being used in the final analysis. Initial pilot studies investigated the influence of the X-ray beam angle on the measurement of the HA angle and confirmed the intraobserver repeatability of each measurement using the OSIRIS software (see Appendix I). To ensure accuracy of measurement, the mean of five measurements was calculated. The measurements from the previous sessions where unseen at the time of each measurement.

2.4 Data Analysis

◊ All data were tested for normal distribution before statistical tests were applied. The 1 sample Kolmogorov-Smirnov test was used to test the discrepancy between the set of values provided and the theoretical, normal distribution. A probability value of $p<0.05$ was chosen to represent the level at which the hypothesis (the sample was drawn from a normal distribution) was rejected.

◊ The student t-test was used to test for significant differences between the means of two normally distributed populations. A value of $p<0.05$ was used to reject the null hypothesis of no difference between population means.

◊ Scatter plots were used to demonstrate the relationship between two variables. Pearson correlation was applied to provide a coefficient (r) to measure the strength of the association for ordinal data. Regression analysis was applied if the distribution was not linear when various models of regression were applied (logarithmic, exponential, power) to determine the strongest model of association. R and R^2 values were given to measure the strength of an association.

◊ Differences in the distribution of nominal or interval data between groups were observed with the aid of contingency tables and Chi-squared tests applied to test the differences in distributions. A value of $p<0.05$ was accepted to reject the null hypothesis of no difference in distribution between groups.

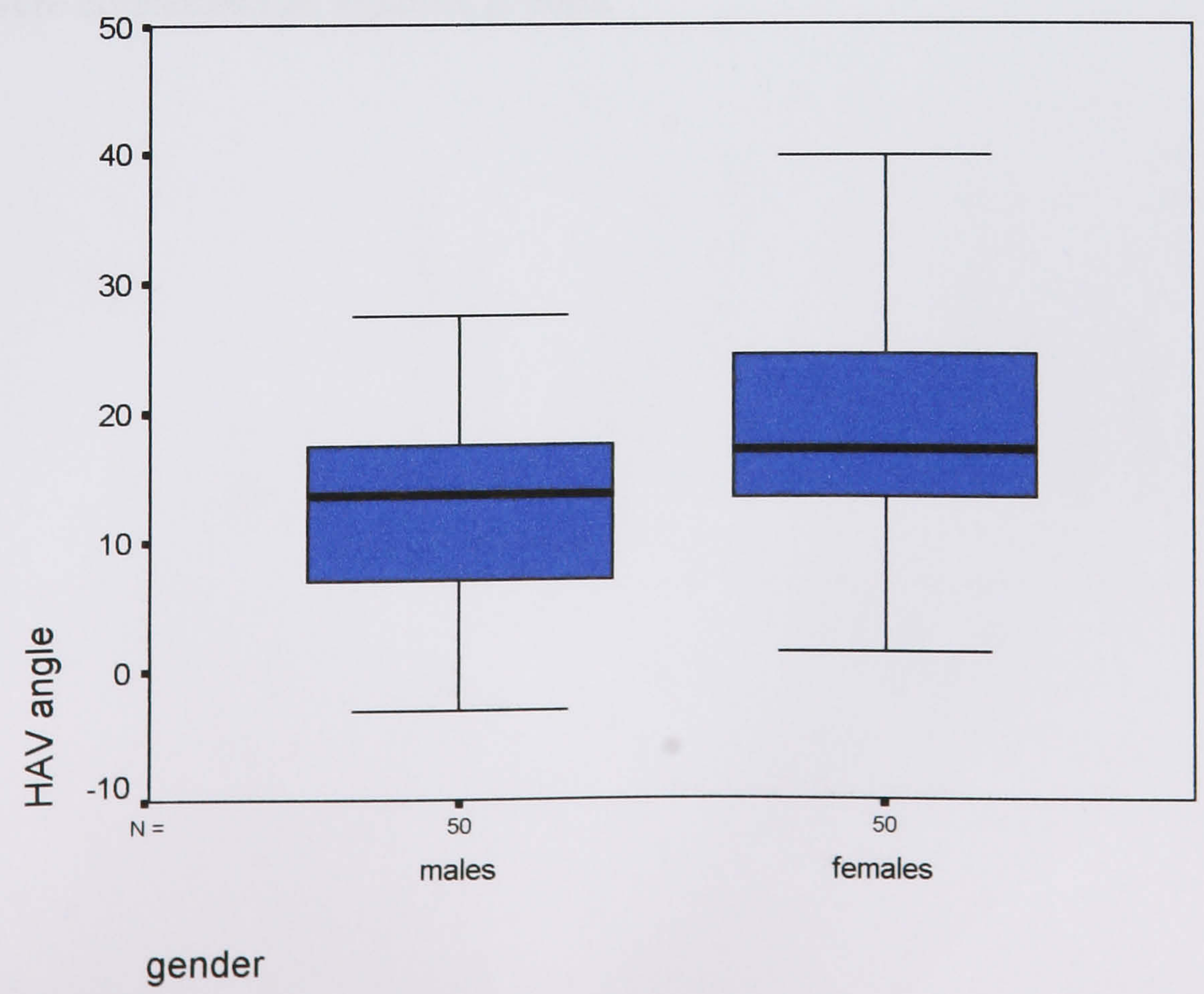
2.5 Results

All data were tested using a one-sample Kolmogorov-Smirnov test for normality. In each case, data were normally distributed and therefore parametric tests were undertaken.

The mean age of female and male patients included were 29 years and 30 years respectively. There was no significant difference between the sexes for age ($p = 0.482$).

Figure 15 shows the box plot for male and female HAV angles with the median angle for each gender highlighted. The upper and lower borders of the box show the 75th and 25th percentiles respectively. The upper and lower bars represent the largest and smallest values for HAV angle, that are not outliers or extreme scores. There was a significant difference between the HAV angle for males and females when the means were tested using a t-test ($p = 0.001$).

Figure 15 showing male and female HA angles



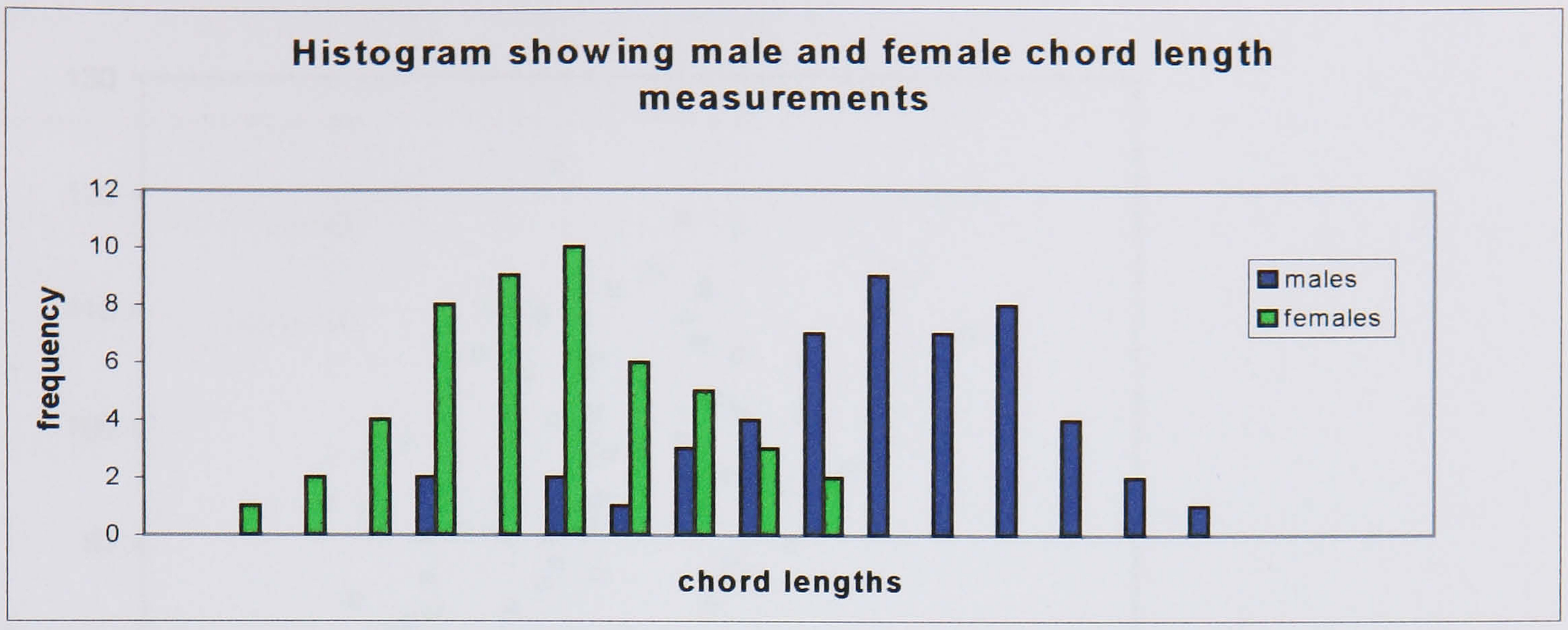
A power calculation was carried out retrospectively to determine probability of a type II error given the sample size (ie. when the null hypothesis is false but the test fails to reject it). With a mean (standard deviation) HAV angle for the males of 12.9° (7.5°) and for the females a mean of 18.3° (8.1°), and a sample size of 50 in each group, there was a 93% chance of correctly detecting a statistically significant result.

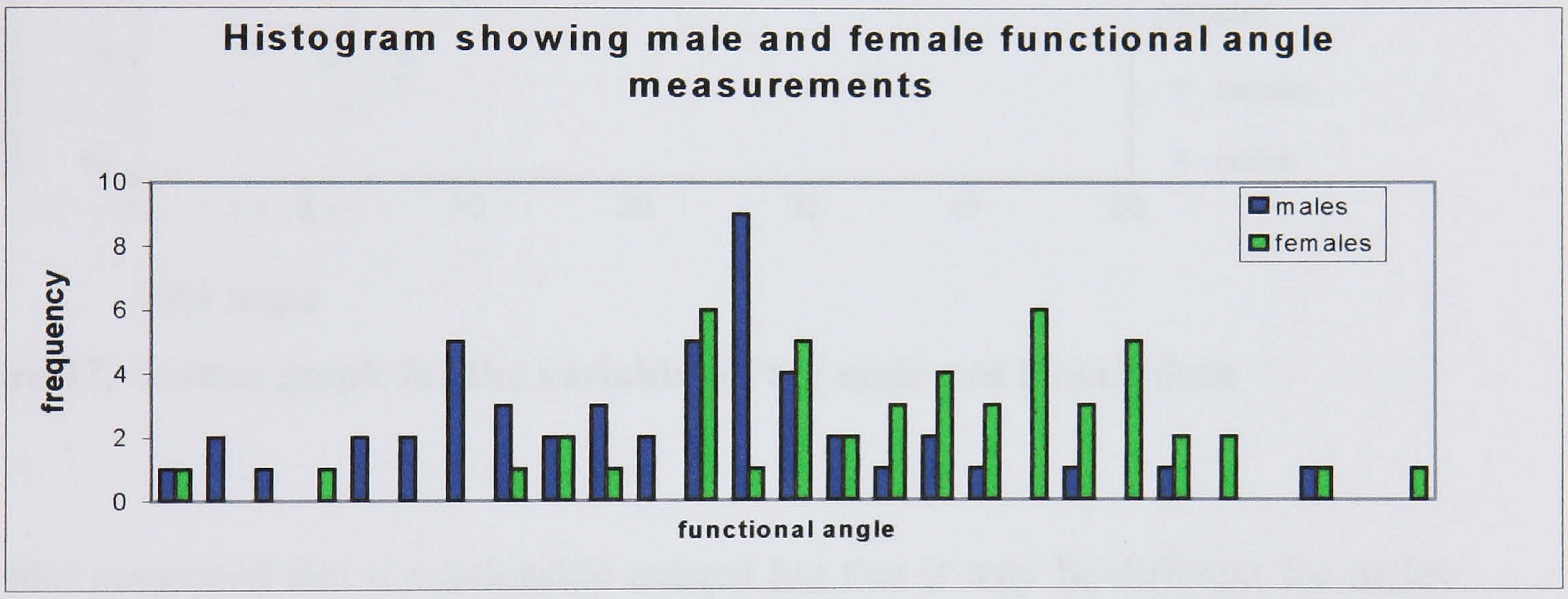
2.51 Metatarsal head shape

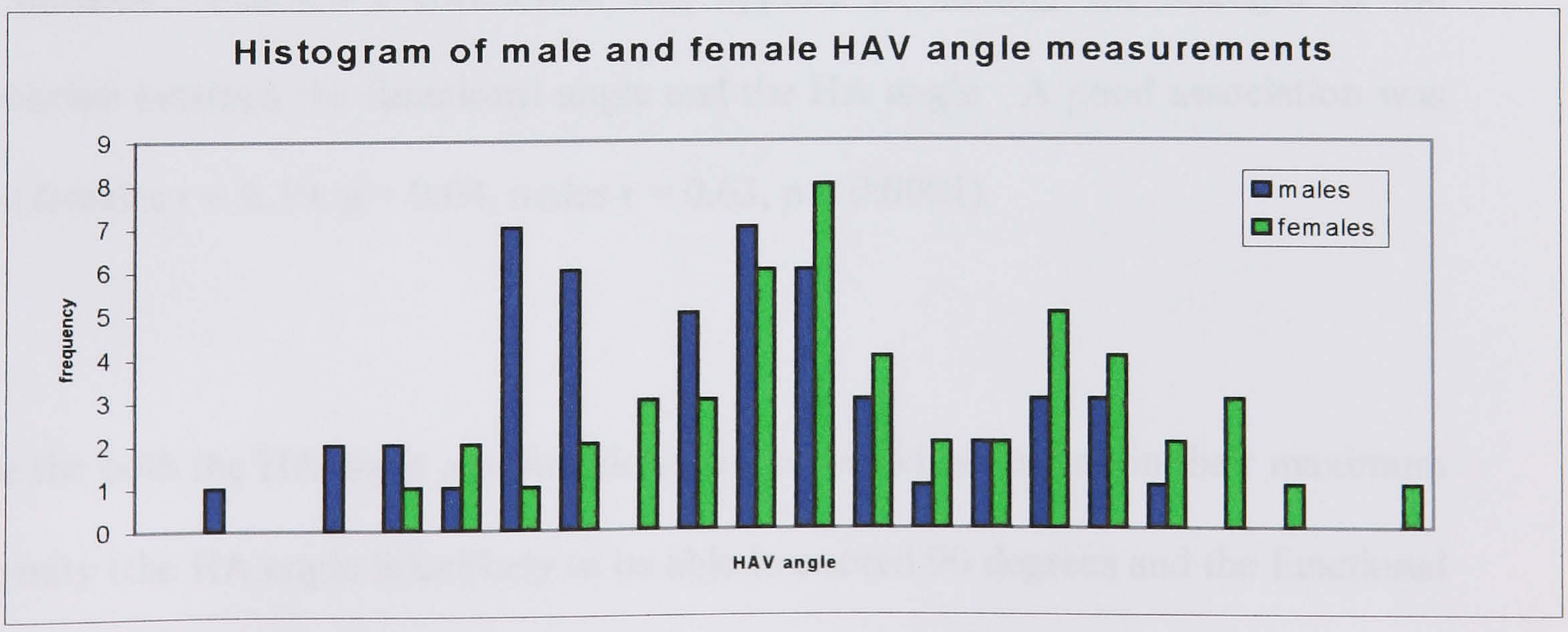
The mean functional angle in females was 99.83° compared to 89.5° in males. This was a significant difference ($p < 0.001$) and figure 13 shows how the distribution of the both the functional angle, chord length and HAV angle differed for males and females.

Observation of the histograms suggested differences between the sexes for each variable. In order to study the relationship between the measurements, males and females were considered as separate groups.

Figure 16. shows the comparison of male and female data for chord length, functional angle and HAV angles.







The relationship between the functional angle and the HA angle for males and females was scrutinised by means of a scatter plot (figure 17).

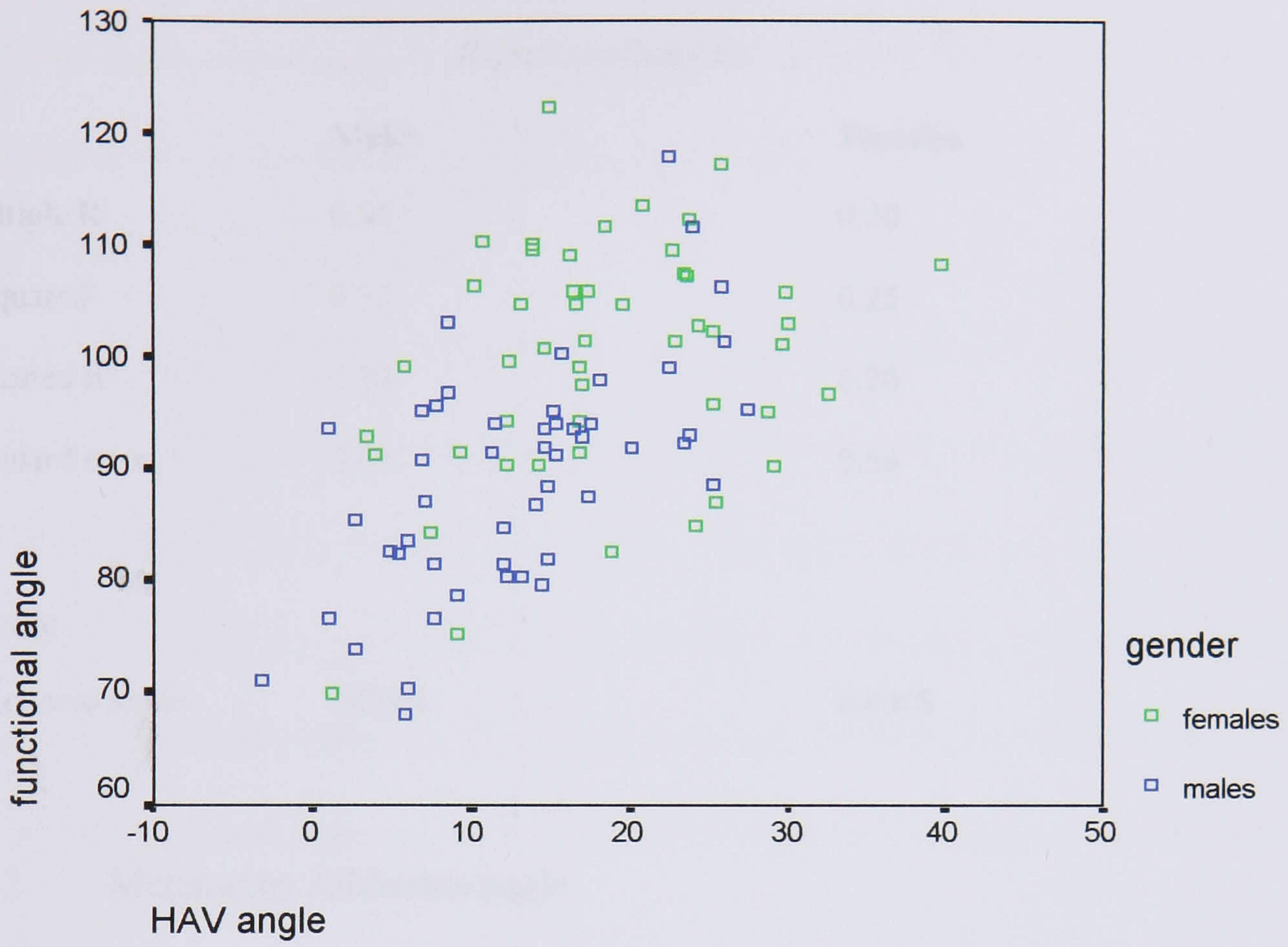


Figure 17. Scatter graph for the variables of the male and female data

The plot suggested that a relationship existed but that it may be different for males and females. Pearson r correlation was applied to identify the strength of the association between the functional angle and the HA angle. A good association was seen (females r = 0.39, p = 0.04, males r = 0.63, p < 0.0001).

Since the both the HA angle and functional angle would be limited in their maximum deformity (the HA angle is unlikely to be able to exceed 90 degrees and the functional angle will be less than 360 degrees) the data may not be linear, so further analysis using data transformation of the functional angle to logarithms was applied. This showed no improvement in the regression statistics for men, but an improved r-squared value for females (table 4).

Table 4 Logarithmic regression analysis

Regression Statistics

	Males	Females
Multiple R	0.56	0.50
R squared	0.32	0.25
Adjusted R^2	0.29	0.20
Standard error	0.69	0.56
P-value		
Functional angle	0.0001	0.0008

2.52 Metatarsus Adductus angle

In five of the males and one of the female radiographs, the tarsal area was obscured so that the MA angle was not measured.

A frequency histogram was constructed to demonstrate the distribution of the metatarsus adductus angle (figure 18).

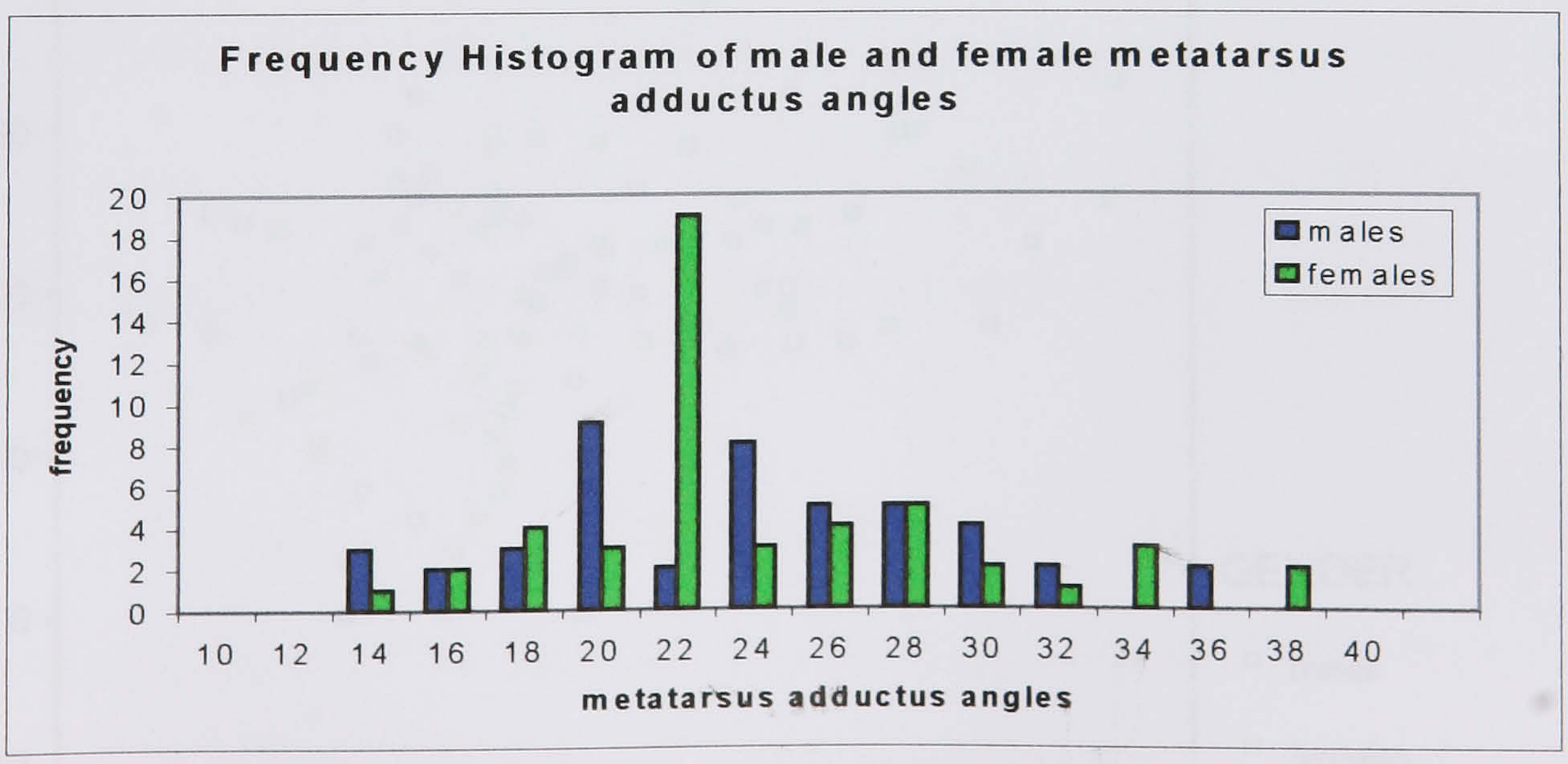
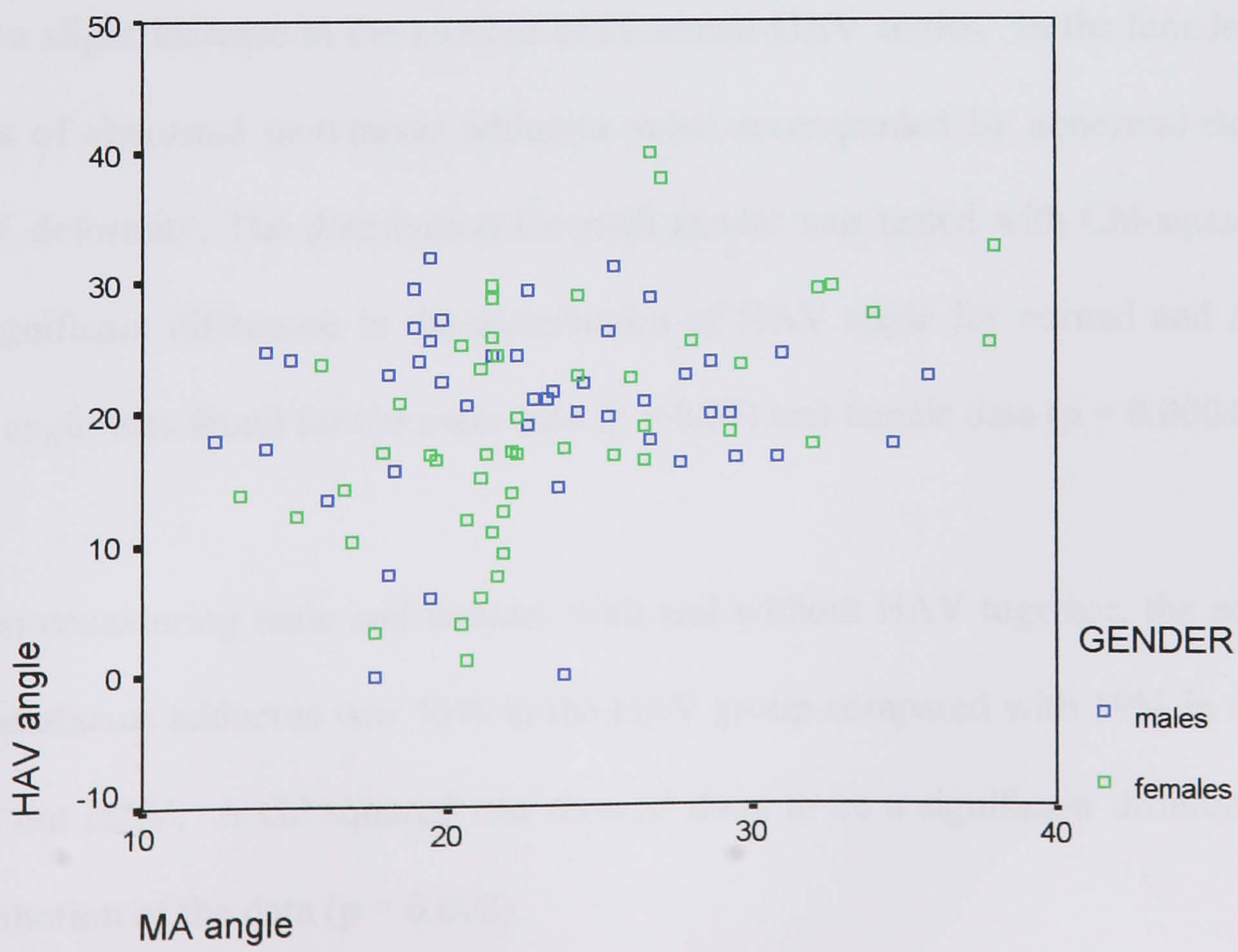


Figure 18. Frequency histogram of male and females MA angles

There appeared to be little difference in the distribution of the metatarsus angle between males and females. This was assessed using a student t-test. The mean MA angle for males was 22.91 degrees and for females was 23.3 degrees. This was not a significant difference between the sexes ($p = 0.73$).

A scatter graph (figure 19) of the metatarsus adductus and HAV measurements suggested that a positive trend existed between the measurements for the female data and to a lesser extent for the male data. The association was tested with Pearson correlation. A definite association was identified for females ($r = 0.53$, $p < 0.001$) and males ($r = 0.48$, $p < 0.001$). The coefficient did not improve with further models of regression analysis although the relationship would not be expected to be linear.

Figure 19. Scatter plot of HAV angle vs MA angle for males and females



A contingency table (see table 5) was created identifying the number of cases of normal ($<24^0$) and abnormal metatarsus adductus ($>24^0$) with the number of cases of normal and abnormal HAV angles.

Table 5. Contingency table for abnormal metatarsus adductus (MA) angles ($>24^0$) and abnormal HAV angles ($>16^0$)

Gender	Male				Female			
MA angle	$\leq 24^0$		$>24^0$		$\leq 24^0$		$>24^0$	
HAV angle	$\leq 15^0$	$>15^0$	$\leq 15^0$	$>15^0$	$\leq 15^0$	$>15^0$	$\leq 15^0$	$>15^0$
Count	21	8	7	11	16	16	0	17

In the male data, there appeared to be some variation in the frequency of HAV deformity, but with most cases of normal metatarsus adductus angles also having a normal HAV angle. When the metatarsus adductus angle was abnormal, there was only a slight increase in the number of abnormal HAV angles. In the female data, all cases of abnormal metatarsus adductus were accompanied by abnormal degrees of HAV deformity. The distribution for each gender was tested with Chi-squared tests. A significant difference in the distribution of HAV angle for normal and abnormal MA angle was found for the male data ($p = 0.01$) and female data ($p = 0.0004$).

When considering male and females with and without HAV together, the prevalence of metatarsus adductus was 55% in the HAV group compared with 19% in the group with out HAV. A chi squared test showed there to be a significant difference in the distribution of the data ($p = 0.002$).

2.53 The Proximal Articular Set Angle

For the 50 male radiographs, the mean PASA was 4.52 degrees. For the 50 female radiographs, the mean PASA was 5.47 degrees. A 2-tailed t-test showed that there was no significant difference between the PASA for males and females ($p = 0.27$).

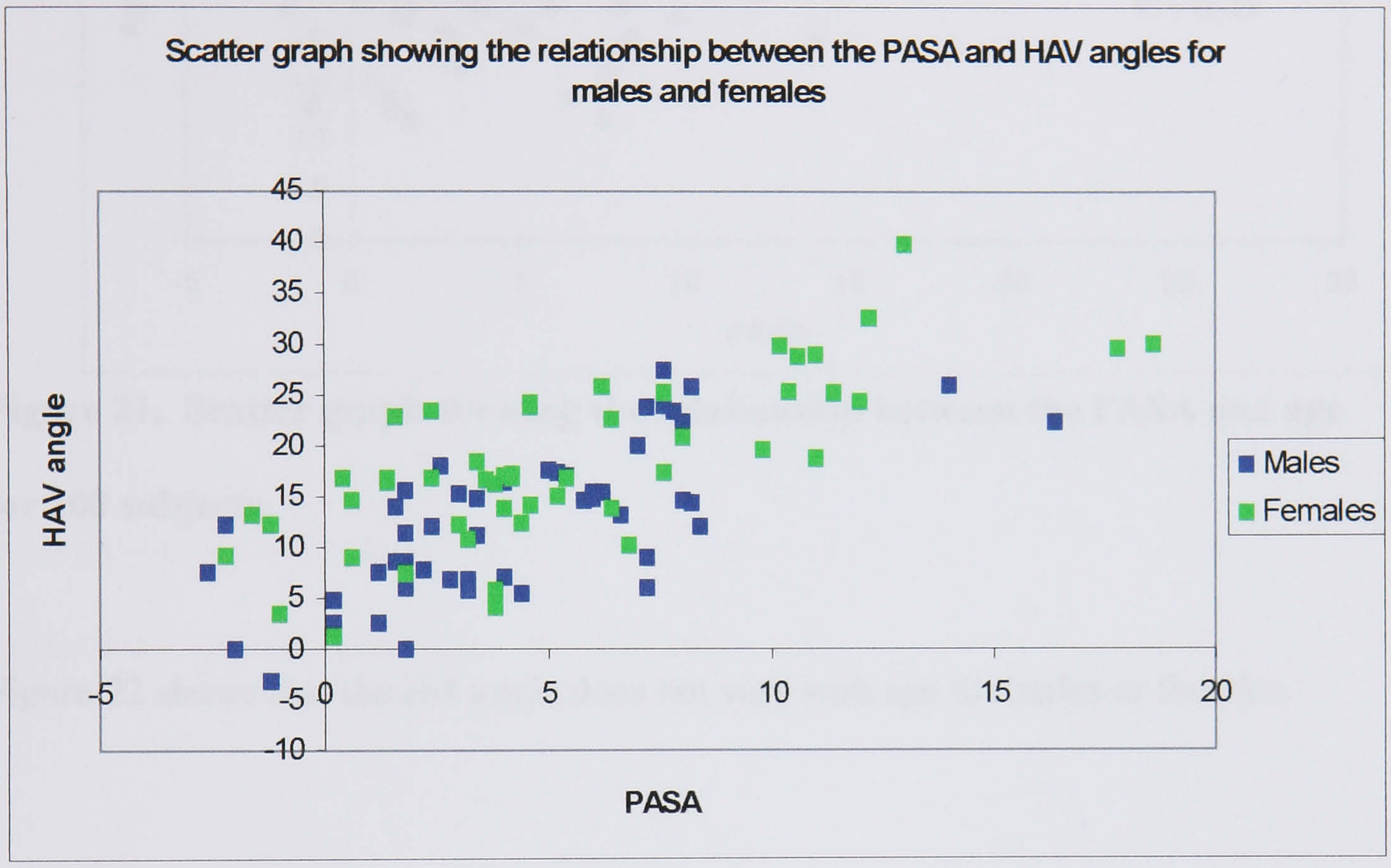
The mean PASA for subjects without HAV (ie. <16 degs) was 5 degrees, range –2.6 to 8.6 degrees.

The relationship between the PASA and HAV angle is shown in figure 19. A positive correlation appears to exist.

Pearson correlation demonstrated a definite correlation ($r = 0.72$, $p < 0.05$) for the 100 patients. There appeared to be little difference in the relationship between males and females and this was confirmed through observation of the correlation coefficients of $r = 0.72$, $p < 0.05$ (males) and $r = 0.74$, $p < 0.05$ (females).

Observation of the raw data suggested a threshold of 7.6 degrees of the PASA. In the 27 subjects with a PASA of greater than 7.6 degrees, only one subject had a normal HAV angle.

Figure 20. Scatter graph showing the correlation between the HAV angle and the PASA for males and females.



The relationship between the variables with age was also considered. None of the variables appeared to show a change with age. No correlation was found between the functional angle and age for either sex when tested by Pearson correlation (males: $r = 0.2$, $p = 0.36$; females: $r = 0.13$, $p = 0.36$). The scatter graph shown in figure 21 suggests that no linear relationship exists for the PASA with age.

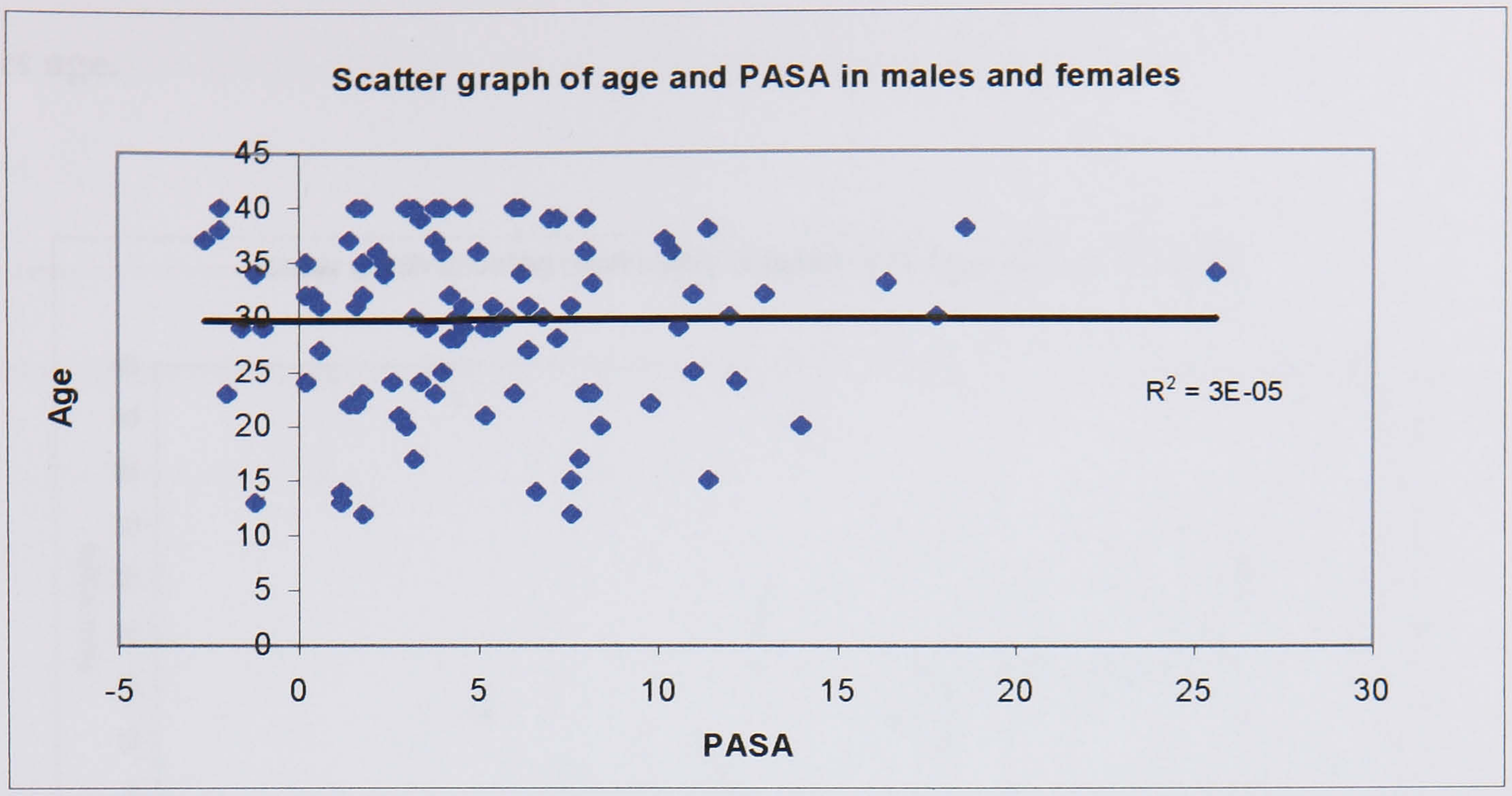
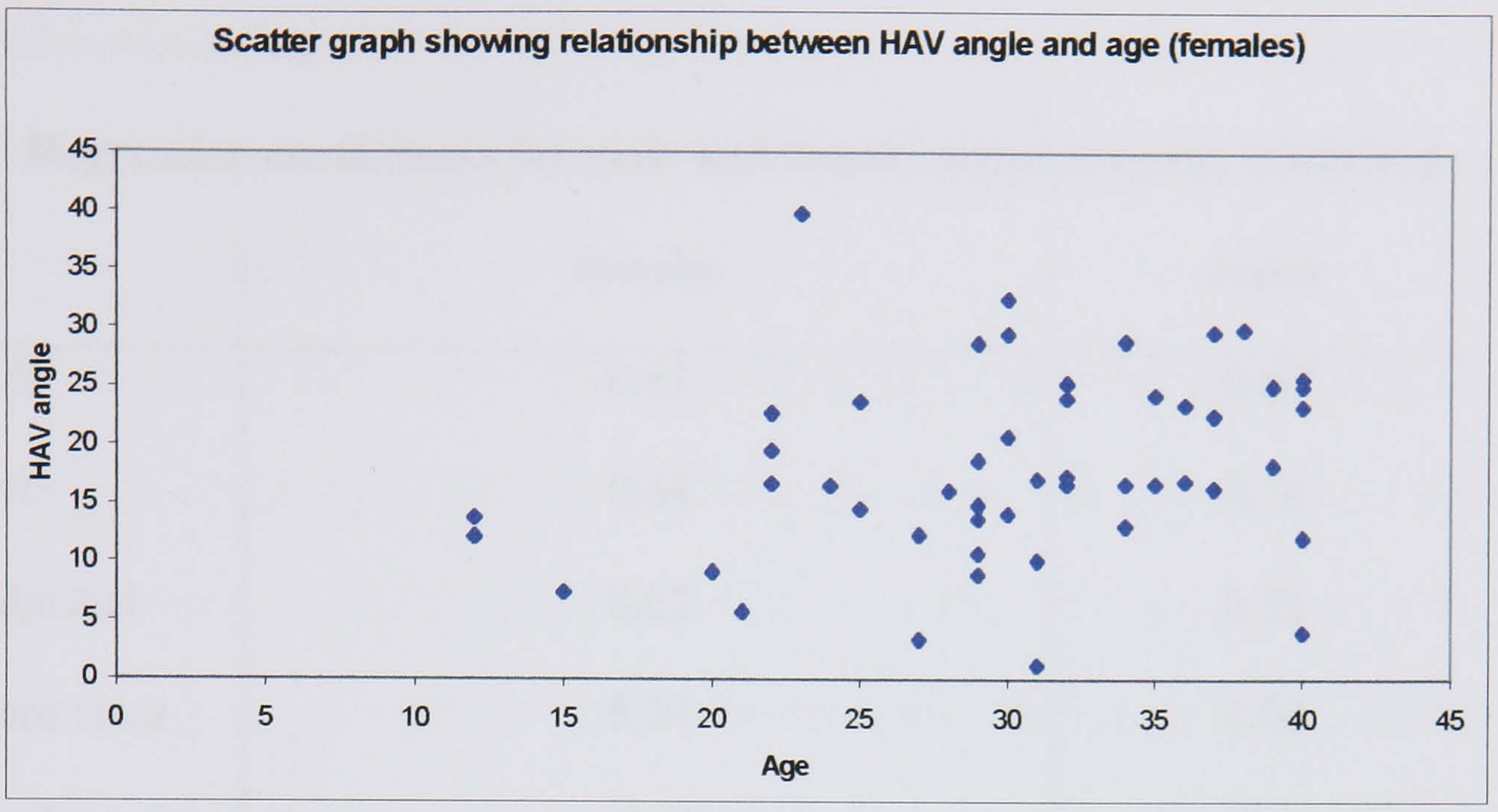
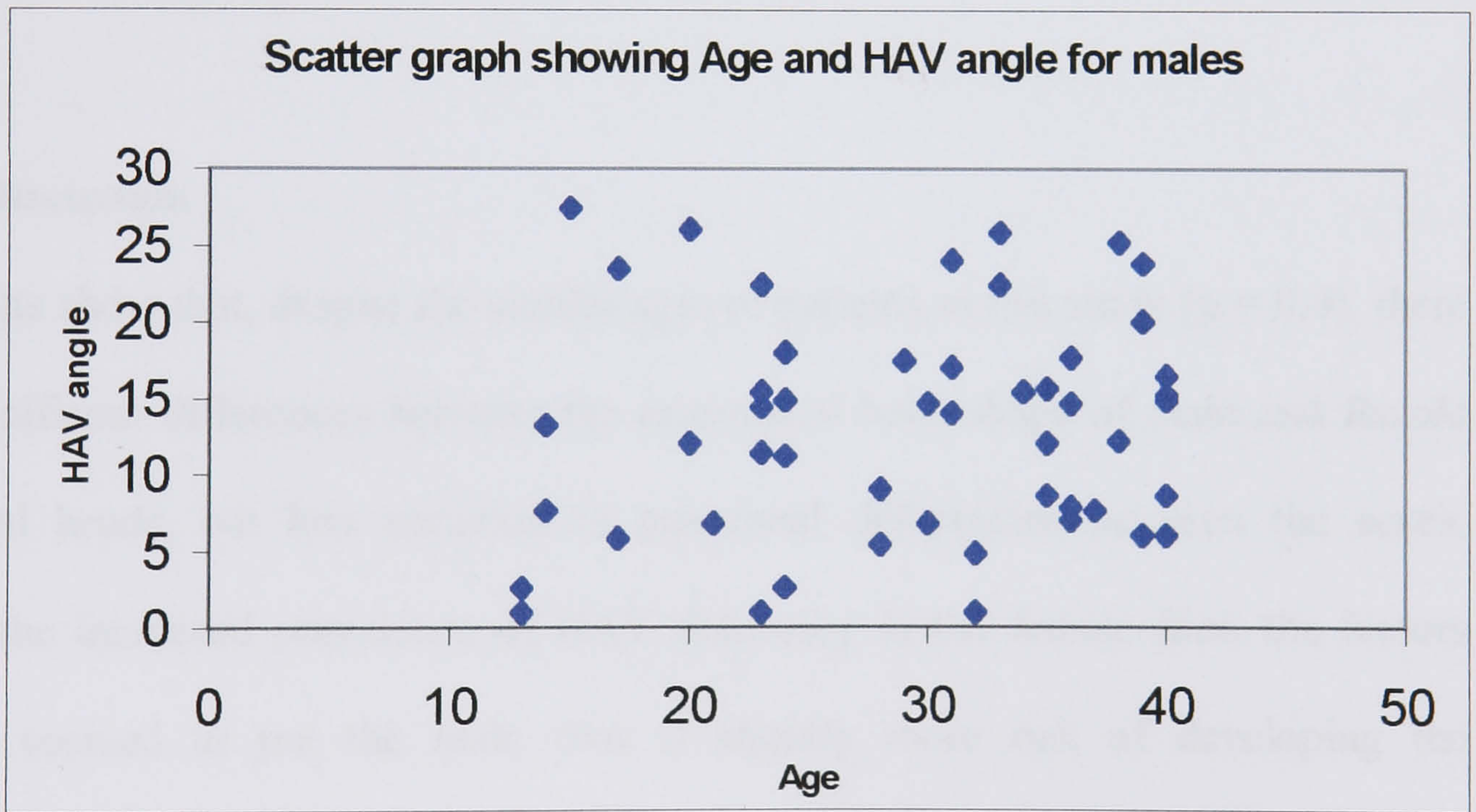


Figure 21. Scatter graph showing the relationship between the PASA and age for 100 subjects.

Figure 22 shows that the HA angle does not vary with age for males or females.

Figure 22. Scatter plots showing the relationship between HAV angle and subject age.





Finally the measurements were combined to test the affect of all three conditions (metatarsal head shape, MA and PASA) occurring together in males and females. Multiple regression analysis was applied and different models tested. Table 6 shows the best regression coefficient achieved when all the data was combined. Thus the relationship between the MA angle, PASA and the logarithm of the functional angle were regressed against the HA angle. The males achieved a higher R^2 value than females.

Table 6. Regression coefficients for male and female measurements combined

	females	males
R	0.81	0.86
R^2	0.64	0.74
R^2 adjusted	0.62	0.71
Standard error	5.24	4.00
P value	<0.05	<0.05

2.6 Discussion

The results show that, despite the similar ages of patients in this study (p = 0.4), there were significant differences between the anatomical bone shape of male and female metatarsal heads, but less variation in positional deformities between the sexes. Despite the increased prevalence of HAV deformity in the female foot, the factors assessed seemed to put the male foot at slightly more risk of developing the deformity, particularly if they occurred together in the same foot.

The HA angle was shown to be greater in females than males and this supports the numerous surveys that have found this same fact (LaPorta et al., 1974; Gould et al., 1980; Kusumoto et al., 1996). Only one study ever has found HAV to be greater in males than females (Hung and Leung, 1985). No relationship between HAV angle and age was found which is surprising as other studies have suggested that HAV angle increases with age (Harris and Beeson, 1998a). Since this study considered a single sample at one point in time, any change with age cannot be detected properly. The age limit of 40 years old taken to prevent the foot being affected by osteoarthritic change also limits the ability of this study to detect change in HA angle with time.

When considering the functional angle measurements, in the variables measured – chord length and functional angle, a significant difference was shown between the sexes. It is unsurprising that chord length varies - men are larger than women and so the difference in bone size between the sexes was expected to be reflected in different chord lengths. It was surprising to find that functional angles should differ between the groups. Men had a smaller functional angle (mean = 89.5°, SE = +/- 1.43) When compared with women (mean = 99.8°, SE = +/- 1.47). The functional angle reflected the amount of deformity that could take place at the joint surface and the method accounted for bone size so that a larger joint does not appear flatter. The larger functional angle was expressed as a rounder joint surface. This result does contrast with the only other trial to consider differences between the sexes, (Gutierrez Carbonell et al., 1998) however that trial only evaluated the shape of the metatarsal using three categories and included unequal numbers of males and females in the groups.

The correlation coefficients show that the functional angle has a greater influence in the development in HAV in men ($r = 0.63$) than women($r = 0.39$). This suggests that when a man has a round metatarsal head he is at a greater risk of deformity than women, but since HAV is more common in women, there must be other risk factors involved that affect the female foot more or combine with the shape of the metatarsal head to increase the risk to women. An example of this may be footwear. A man with a rounder metatarsal head, wearing a shoe with a wide toe-box places little medial pressure against the toe compared to a women with a less rounded metatarsal head wearing a shoe with a narrow/pointed toe-box. The increased medial pressure of the narrow shoe combined with the shape of the metatarsal head may increase the risk in women since such shoes are more likely to be worn by women. It may be that the women who suffer from the worst HAV deformities have a tendency towards a rounded metatarsal head but also wear the more unsuitable shoes.

Hypermobility may be another factor involved. Women are known to be more flexible than men, (Harris and Beeson, 1998a; Beighton et al., 1973) therefore for the same deforming force, the women's deformity may be greater due to the flexibility of the soft tissue structures.

Other authors have suggested that the shape of the 1st metatarsal head will reflect differing functions of that joint. For example, in populations where the women have crouching occupations such as cooking or grinding flour, which requires greater extension of the 1st mtpj, the articular facet on the 1st metatarsal head is extended further dorsally that in the men who have other occupations such as farming and hunting (Molleson, 2001). The shape varies between bipeds and arboreal mammals (Latimer and Lovejoy, 1989; Morton, 1935). In the modern population, differences in foot function between the sexes are less obvious and so it is hard to account for the different shapes for reasons other than genetics or manipulation from footwear in childhood.

The regression coefficient for HA angle with the functional angle for women increased when a logarthmic regression was applied ($R = 0.50$, $R^2=0.25$). A linear relationship was not expected for either sex as both the HAV angle and functional angle have maximum values that can be reached therefore some plateauing of the curve would be expected as the angles increased. Using a wider age range with a potentially wider range of HAV angles may show the relationship more effectively.

The method used in this study was subject to some errors. The functional angle was calculated at the centre of the chord. This was not the highest point of the curve of the metatarsal head in all cases and so may have underestimated the functional angle in such a situation. An initial pilot study on the effect of X-ray beam angle (see Appendix I) showed that when the beam was moved through angles from 15° anterior-posterior to 15° posterior-anterior, the functional angle showed significant differences. These differences occurred for beam angles from 0° to 15° posterior-anterior. For beam angles between 15° anterior-posterior to 0° there was no differences in functional angle. Since the study being undertaken was a review of radiographs, there was no way to control for beam angle. The department that took the radiographs uses a standard positioning of the beam at 15° anterior-posterior but error in positioning the beam may be affect the results of this study.

Also, although the intraobserver repeatability of the measurements was tested, the validity of the method was not. Further study of the validity of the method would be warranted and could be achieved using cadavers. For example, using a 2-dimensional method to assess a 3-dimensional structure is not ideal. The medial – lateral curvature of the metatarsal will not be accurately measured in situations where the metatarsal is rotated when taking the X-ray and different points on the metatarsal head will be view depending upon the angle of declination of the metatarsal. The 1st metatarsal has been described to rotate both externally or internally in HAV deformity (Evans and Lile, 2000; Fox and Firstein, 1989). The method used in this study will measure the transverse curve as it appears on the dorso-plantar film. For future study, it would be interesting to discover if the rotation of the metatarsal affects the apparent curvature of the surface that the metatarsal moves around. For example, if the metatarsal is everted to 90 degrees, the proximal phalanx would be moving around the dorsal-plantar curve of the metatarsal head, which may be a greater curve than the medial-lateral curve and thus the rotation of the metatarsal may be strongly linked to the HAV deformity, reflected through the curvature measured.

In his study, Brahm (1988) had questioned whether the metatarsal head was being remodelled. The lack of arthritic changes led the author to conclude that this was not the case. In this study, osteoarthritic change was an exclusion criteria and so the question of remodelling has to be considered in another way. If remodelling were occurring, a change in functional angle would be expected with increasing age. Analysis of age versus functional angle in men and women showed no relationship. However, as the study was not able to establish a relationship between HAV and age, it is unsurprising that the relationship between functional angle and age could not be detected. A longitudinal study would be suitable for investigating if remodelling can occur in a joint surface.

An association was also identified between the degree of metatarsus adductus and the degree of hallux valgus in male and female subjects. The relationship concurs with the findings of earlier studies (Banks et al., 1994; Griffiths and Palladino, 1992). The study found no difference in the metatarsus adductus angles between males and females ($p=0.73$). Banks *et al* did not test for differences between male and female subjects and did not report the percentage of male and female patients in their study. Griffiths and Palladino tested for differences between the sexes and found no significant differences in the measurements for metatarsus adductus or HAV angles. That no differences in the HAV angle were found was surprising given that most studies demonstrate the high female prevalence of the condition. The lack of a significant difference in HAV measurements may be due to the initial selection criteria which excluded any patient with clinical signs and symptoms of HAV from their study.

La Reaux and Lee (1987) found that 13% of their control group (no HAV) had a metatarsus adductus deformity compared with 35% of their HAV group (female over male ratio = 4:1). The present study had similar findings when considering males and females together (ratio 1:1) with an 18% prevalence of metatarsus adductus in subjects without HAV and a 55% prevalence in subjects with HAV deformity. Pontious *et al* (1994) found that 75.4% of their HAV patients (37 females, 17 males) had a metatarsus adductus deformity. Such a high prevalence is was not explained but since the study group consisted of juvenile patients awaiting surgery, it may be a result of the increased angle seen in children plus the correlation established here between HAV and metatarsus adductus in females.

Our study has shown that the distribution of HAV deformity, when considered in subgroups with and without metatarsus adductus, is significantly different between males and females. In males with a normal metatarsus adductus angle, the majority of subjects also had a normal HAV angle whereas the females had equal numbers of subjects with and without HAV deformity. In both males and females with abnormal metatarsus adductus angles, the frequency of abnormal HAV angles increased but to such an extent in females that all cases of abnormal MA angles were accompanied by abnormal HA angles. HAV deformity can exist in females without metatarsus adductus demonstrating that the deformity has other etiologies, but this study has found that when a metatarsus adductus deformity is present, HAV always accompanies it.

Footwear may be responsible for the correlation between metatarsus adductus and HAV in females. Rothbart suggested that HAV deformity occurs with metatarsus adductus in shoe-wearing populations (Rothbart, 1972). With an adducted first metatarsal, the medial side of the toe-box prevents the hallux from aligning with the metatarsal and relatively abducts the hallux at the metatarsophalangeal joint. The more pointed the toe-box, the greater the abduction at the joint. The footwear worn by the subjects in this study was not known. The subjects were less than 40 years old and given the present trends in footwear today, it is very likely that the women's shoes were more pointed than the men's thus putting a greater medial / abductory force on the hallux.

Also, the increased flexibility of the female foot coupled with a metatarsus adductus deformity may lead to greater risk of HAV deformity than seen in males – the increased joint mobility leading to the joint being less stable when an abductory force is applied.

One error in measuring the MA angle in this study was in the problem that when taking a radiograph of two feet, the X-ray beam falls between the feet and therefore at an angle to the metatarsals. This causes an apparent increase in the MA angle and although does not affect the regression coefficients found, does limit the comparison of actual values to other studies if they used a different method to X-ray the feet.

The data from this study agrees with the findings of earlier studies regarding the normal range of angles for the PASA. LaPorta *et al* had suggested values of 0-8 degrees. This study found a range of –2.6 to 8.6 degrees in subjects without HAV deformity. Steel *et al* (1980) found values from 0-15 degrees in their population, which closely mirrors the range of –2.6 to 19 degrees found across the study group used this study. The wide range found in the cadaver study of –3 to 26 degrees was not found although there was a similar mean to the present study (6 degrees versus 5 degrees) (Richardson et al., 1993). The age of the cadavers used by Richardson *et al* was not given, however if typical, they were likely to be elderly subjects and may have a greater range of HAV deformity or long standing deformity which may account for the increased PASA angles found.

The study has shown that males and females have the same PASA despite having different HAV angles. The association between PASA and HAV was similar between the sexes and it is possible that the HAV angle is causing the PASA angle to change. A large HAV angle may cause increased lateral forces on the metatarsal head and lead to a change in the PASA over time. This study did not investigate progression of the angle with time but by considering the PASA angle and age, found that the PASA and patient age were not related. However by limiting the age of the patients to 40 years may obscure other relationships. A longitudinal study of HAV deformity and PASA would required to study this. If the HAV angle was causing the PASA angle to change, it is more likely that a male to female difference would have been seen, mimicking the male / female differences in HAV angle.

This study found that a threshold of PASA was related to HAV deformity. When the PASA exceeded 7.6 degrees, all but one of the subjects had HAV deformity greater than 15 degrees.

Overall, when the three conditions of metatarsal head shape, MA angle and PASA were combined, the regression coefficients showed a slightly stronger association men than women ($R = 0.86$, $R^2= 0.74$ vs $R = 0.81$, $R^2= 0.64$). These bony shapes and positions are obviously strongly related to HAV deformity in men which is comparatively rare, but other factors may also be involved such as subtalar pronation. In women, other factors peculiar to women would appear to be more certainly involved since the condition is so much more prevalent amongst them. It is hypothesised that footwear and hypermobility are such factors that cause HAV deformity in a foot that is structurally at risk.

2.7 Conclusion

This study has demonstrated that a relationship exists between the functional angle of the 1st metatarsal head and hallux abductovalgus. A rounder metatarsal head is associated with an increased HAV deformity. The relationship is stronger in males than it is in females and a significant difference in the functional angle was found between the sexes.

The MA angle and PASA did not differ between males and females. In women, an abnormally increased MA angle was always associated with an abnormal HAV angle, but this was not the case in men. A threshold of 7.6 degrees, at the extreme of the normal range of PASA angles (0-8°) was found to be associated with abnormal HAV angles in males and females.

The bony shapes and positions investigated appeared to show stronger associations for the occurrence of HAV deformity in males than females. Further factors peculiar to the female foot are therefore suggested to account for the increased female prevalence of HAV deformity.

2.8 Publications and Presentstions

This study resulted in the publication of three articles on the relationship between the bone shape and HAV deformity (see Appendix II):

- Ferrari J and Malone-Lee J. A study of the relationship of the shape of the metatarsal head and hallux abductovalgus deformity. Foot & Ankle International. 23 (3):236-242, 2002.
- Ferrari J and Malone-Lee J. A study of the relationship between the proximal articular set angle and hallux abductovalgus. J American Podiatric Medical Association. 92(6):331-335, 2002.
- Ferrari J and Malone-Lee J. A study of the relationship between Metatarsus Adductus and Hallux abductovalgus. J Foot Surgery. February 2003.
- Faculty of Surgical Podiatrists, Annual Conference, Warwick University, October 2002 – presentation: "Is the female foot predisposed to HAV deformity – a radiographic study".

CHAPTER 3 A 3-DIMENSIONAL STUDY OF THE SIZE AND SHAPE DIFFERENCES BETWEEN MALE AND FEMALE FOOT BONES

3. A 3-DIMENSIONAL STUDY OF THE SIZE AND SHAPE DIFFERENCES BETWEEN MALE AND FEMALE FOOT BONES

3.1 Introduction

The radiographic studies in chapter two found that the shape of the first metatarsal head in females has a greater functional angle than males but that the proximal articular set angle does not vary between the sexes. This difference, along with positional changes of the metatarsal such as metatarsus adductus, may be associated with the development of HAV deformity. A difference in the shape of the bones in the medial column of the foot proximal to the metatarsal, or in the articular surfaces, may also result in the positional changes of the first metatarsal, that lead to HAV. Alternatively, the changes may be as a result of the HAV deformity. Therefore further study in a different population is required. The study of differences between male and female bones have been undertaken in the fields of anthropology and forensic science, but an association between any differences found and hallux abductovalgus deformity has never previously been sought.

The foot bones provide essential information on the locomotion and habits of an individual. Extensive studies of the feet have been undertaken in anthropology since bipedal characteristics can be identified in the rearfoot, whilst grasping and arboreal dwelling may be reflected in the forefoot. Thus the theoretical evolution of the ape to the bipedal human has been described in the feet from primate species several million years old through to the modern day. Despite the in-depth knowledge of developing bipeds, few studies have considered whether male and female feet are the same in aspects other than size. Forensic studies have focused on size differences in an effort to estimate the height or sex of an individual for purposes of identification.

In HAV deformity, widening of the forefoot occurs with the development of an increased 1st-2nd intermetatarsal angle and adduction of the 1st metatarsal.(Piggott, 1960) Only in cases of metatarsus adductus deformity does the IM angle not increase since, in this situation, all the metatarsals are adducted rather than just the 1st metatarsal (see fig 23). The adducted first metatarsal position could be related to the anatomical structure of any of the bones in the medial column of the foot (medial cuneiform, navicular, and talus) that results in a more medially facing 1st metatarsocuniform joint.

Figure 23. An adducted 1st metatarsal bone with a low IM angle due to adduction of the lesser metatarsals.

The adducted position of the 1st metatarsal, so frequently seen with HAV deformity, has been described amongst the evolutionary changes of the foot.* One of the first

*In anthropology the movements of the bones are described with reference to the midline of the body. In podiatry, the midline of the foot is used.

primate species thought to be capable of bipedal activities was *Oreopithecius bambolii.* This species was initially thought to be a vertical climber with ape-like feet, but after further study, features of the spine, pelvis and femur were suggestive of bipedal characteristics.(Kohler and Moya-Sola, 1997) The feet were described as having features consistent with weightbearing. The line of leverage was described as falling between the 1st and 2nd metatarsals due to abduction of the lesser metatarsals, whereas in primates the line of leverage usually falls through the 3rd metatarsal (see figure 24).

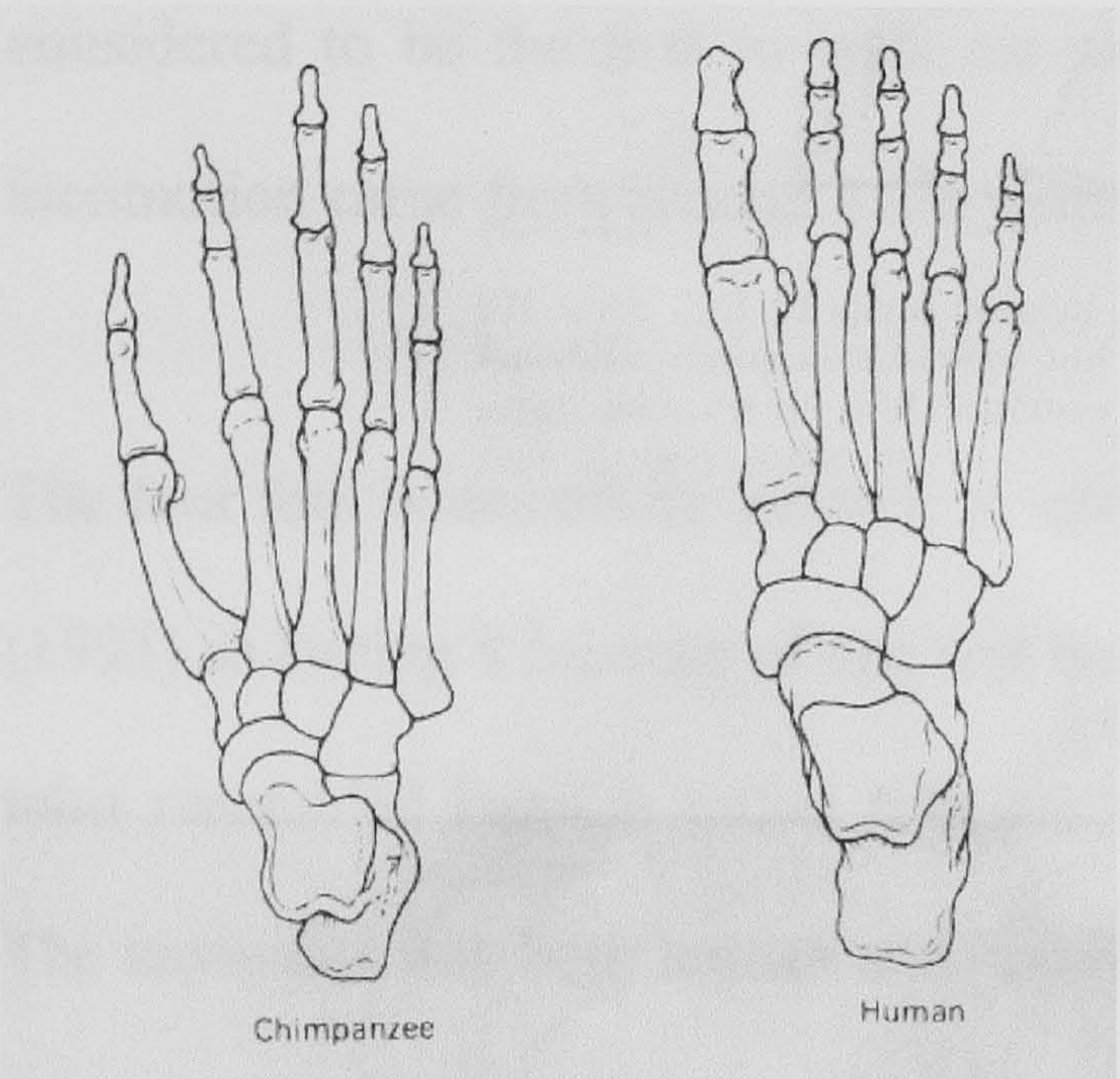


Figure 24. showing the differences between a human and a chimps foot.

The cuboid was small, the intermediate and lateral cuneiforms had large joint surfaces and the 2nd metatarsal was wedged between the cuneiforms indicating that the majority of weightbearing force was transmitted medially whereas in apes, the force is transmitted down the lateral side of the foot. The metatarsals were short with minimal torsion compared to primates. The calcaneocuboid joint and cubometatarsal joints were flat, indicating very little rotatory movement was possible such as would be more important in grasping. The 1st metatarsal in this species was considered to be adducted and used to buttress the foot against the medial weightbearing forces when standing. In modern humans, a rigid plantarflexed 1st metatarsal is considered more useful for buttressing such forces compared with the adducted metatarsal, which is generally flexible and unstable. As the digit was initially divergent for grasping in *Oreopithecius bambolii*, its change of role to one of stabilisation may be in keeping with the modern foot.

Oreopithecius bambolii was considered to be from the Upper Miocene period and thus would have existed around 10 million years ago. The species more frequently considered to be the first to walk on two feet as part of their principal method of locomotion came from around 3.5m years ago, called *Australopithecus africanus*.

The four foot bones of the fossil of *A. africanus* were described by Clarke and Tobias (1995) as having a mixture of ape and human features.(Clarke and Tobias, 1995) The talus resembled humans rather than apes being short with a small talar neck angle. The navicular was both human and ape-like, with a concavo-convex medial facet for the medial cuneiform whilst the direction of the intermediate and lateral cuneiform facets suggested the forefoot was abducted. The medial cuneiform facet suggested that the 1st metatarsal would be adducted and showed features of a mobile joint to allow the foot to be used in grasping (see fig 25).

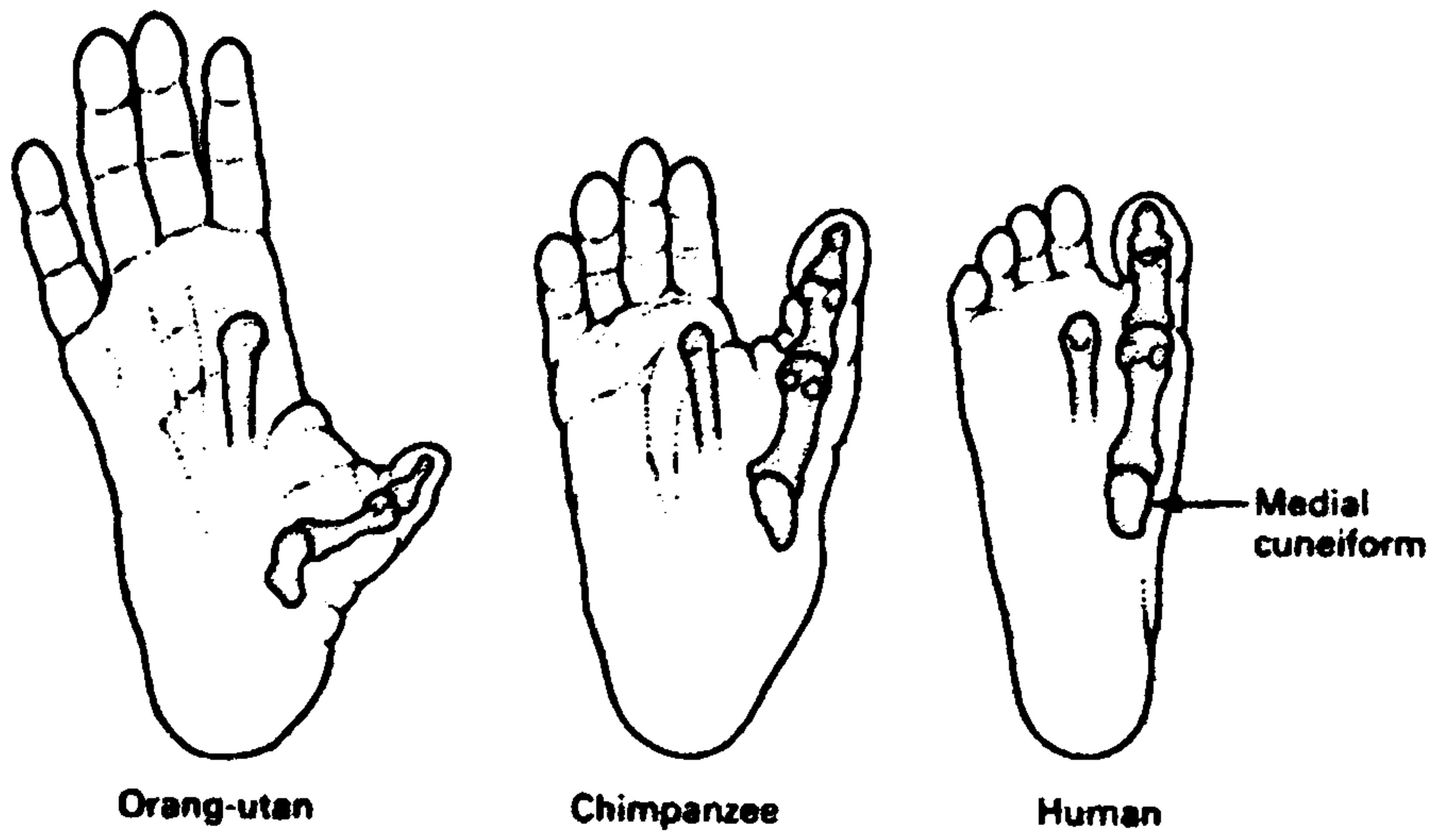


Figure 25. Variation in the 1st metatarsocuneiform joint resulting in a difference in alignment of the metatarsal between species.

However, a single L-shaped facet was found on the lateral surface of the medial cuneiform, contradicting the grasping nature of the forefoot since it is described as a defining human feature.(Clarke and Tobias, 1995) The L-shaped facet suggests a less divergent 1st ray, created by contact between the intermediate cuneiform and 2nd metatarsal. Clarke and Tobias suggested that the 1st metatarsal could be locked into an abducted position for weightbearing. The foot therefore appeared to have both human and ape-like features - the rearfoot showed similarities to humans which would allow it to weight-bear effectively whilst the forefoot was more ape-like with the divergent 1st metatarsal still being present to aid climbing and grasping, but also able to resist standing. When considering the position of the metatarsal head, Duncan *et al* (1994) also found *A. afarensis* to have a metatarsal head shape with features between homo and apes.(Duncan et al., 1994) It is of note that these authors are the first to attempt measuring bones using a computer assisted device, but the measurements do not appear to be 3-dimensional.

The fossil Olduvai Hominid 8 (OH8) (see figure 26), found in Tanzania, is dated at around 1.7 million years old and is of the species *Homo habilis*. There has been intense debate regarding the human or ape-like status of this fossil. The talus was initially thought to be human-like but later it was disputed that it was closer to the orangutan.(Oxnard and Lisowski, 1980) The foot was initially thought to be from an elderly female but was later described as being from a sub-adult aged 13-14 years old.(Susman and Stern, 1982) Lewis (1972) was surprised at the primitive nature of the metatarsocuneiform joint.(Lewis, 1972b) Lewis described the superior convexity and inferior concavity of the cuneiform and the concavity of the reciprocal surface of the metatarsal as being unseen in humans, but again described a locking mechanism that could occur at the joints to aid stabilisation either in grasping or weightbearing. Susman and Stern (1982) thought the shape of the first metatarsocuneiform joint was human-like with the distal surface of the medial cuneiform facing less medially and it was suggested that the 1st metatarsal would be non-divergent. The robustness of the foot bones suggested weightbearing capacity with minimal torsion whilst the hand bones had grasping characteristics. The fibula was considered to be very human-like whilst the tibia had features more consistent with the apes. Thus in this fossil, the rate of evolutionary change appeared to be different for the medial and lateral portions of the leg whereas earlier fossils seemed to have a faster rate of evolution in the rearfoot for weightbearing compared with the forefoot which retained grasping features.

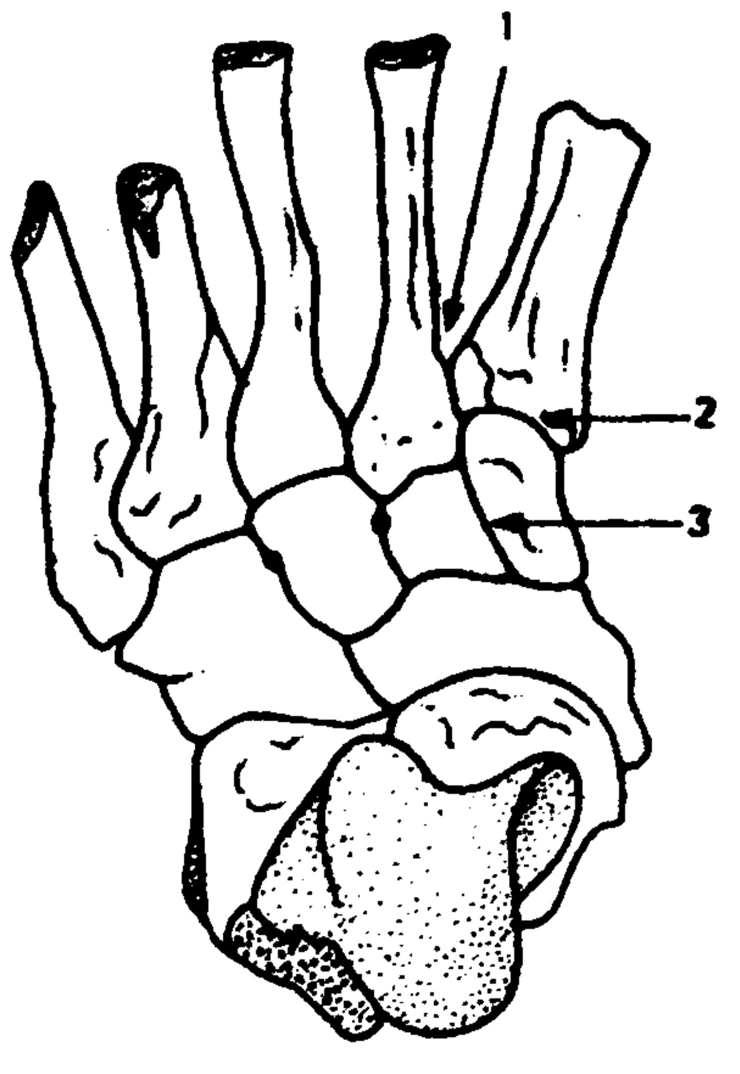


Figure 26 showing the Olduvai Hominid 8 with :

1. **Articulation between the 1st and 2nd metatarsals.**
2. **A forward facing 1st metatarsocuneiform joint**
3. **A single articulation between the medial and intermediate cuneiforms**

In a comparative study of species including OH8, Kidd *et al* (1996) separated the groups into males and females although the numbers of bones involved was quite small – a maximum of 20 males and females in each group.(Kidd et al., 1996) The measurements for Kidd's study were taken from digitised photographs and the results stated that there were no differences between the sexes of each species except for the calcaneal facet angle in orangutans. The analysis included the data separated into genders for the multivariate analysis and graphical representation (cluster analysis) of the data showed that the male and female bones had distinct groupings, however the differences were not sufficiently great that they masked the differences between the species being compared. The findings suggested that the OH8 talus was similar to the orangutan in some, but not in all of its features. The navicular was ape-like rather than human-like. The cuboid was closer to the humans than apes. The calcaneum was distinct from the other species. Kidd *et al* suggested that the increased talar neck angle would produce an adducted 1st metatarsal. This was in contrast to the earlier view and would then mean that *Homo habilis* and *A. afarensis*, and in particular the female sex, were still lacking in the evolutionary changes necessary to stabilise the medial column of the foot against the ground. Kidd described a bony locking mechanism that was present between the OH8 cuboid and calcaneum that is also found in the modern human. This locking mechanism gives stability and rigidity to the foot (Root et al., 1977a) and alongside the human-like cuboid in OH8 would again suggest that the evolutionary changes towards bipedalism were occurring at a faster pace on the lateral border of the foot compared to the medial border which still retained, at this stage, the adducted 1st metatarsal.

In a later study by Kidd (2002), differences between the sexes of human foot bones from varying populations were identified and the authors stated that "*individual analyses place size and sex differences as greater than geographic differences*".(Kidd and Oxnard, 2002) The differences in the bones between genders were not explained.

Younger than *H. habilis*, the Neandertals lived between 35,000-100,000 years ago. The skeleton of Neandertals have been compared with *H. habilis*.(Oxnard and Lisowski, 1980) The Neandertal talus was found to be indistinguishable from the human range in many dimensions, although it had larger joint surfaces after accounting for size (Rhoads and Trinkaus 1977) (see figure 27).

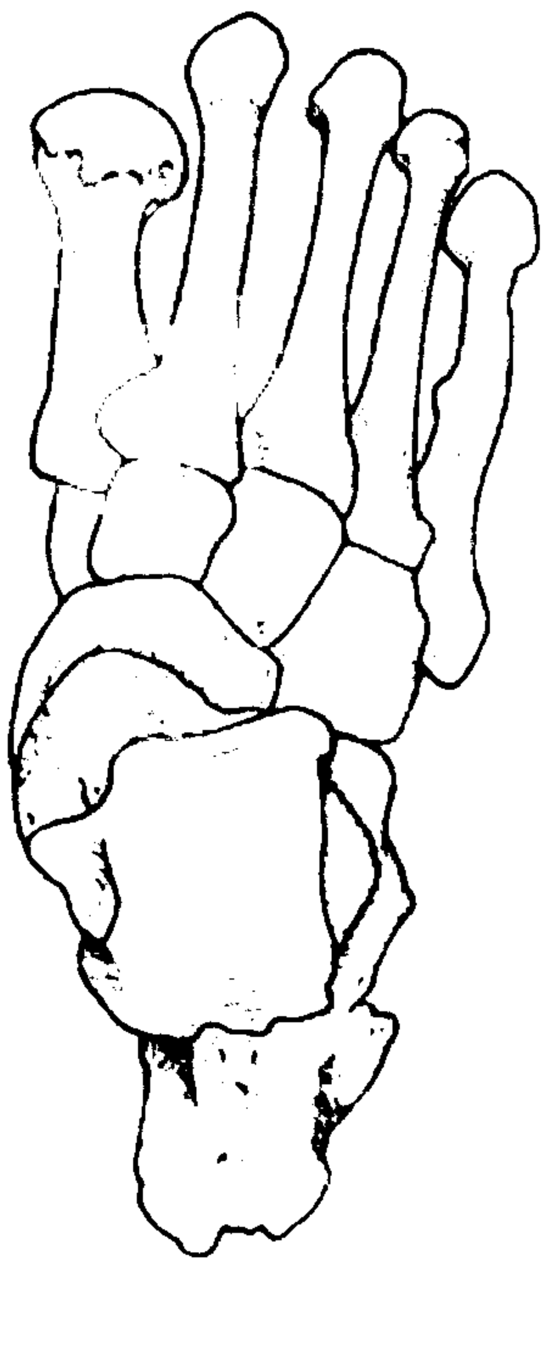


Figure 27. Neandertal foot skeleton

The study of several fossil remains concluded that the 1st metatarsal was no longer divergent and lacked the torsion seen in apes. Rhoads and Trinkaus (1983) reported that modern humans can have a concavity of the metatarsocuneiform joint and this does not necessarily result in adduction of the metatarsal.(Rhoads and Trinkaus, 1977) The Neandertal skeleton had a similar concavity and was considered to have a non-divergent, abducted 1st metatarsal. When a concavity of the base of the metatarsal was described in the foot of *A. afarensis*, it was considered to produce adduction of the 1st metatarsal.(Clarke and Tobias, 1995)

When considering the orientation of the articular facets, the author suggested that the Neandertals have greater lateral deviation of the distal articulation of the 1st metatarsal for the proximal phalanx. This lateral deviation (increased Proximal Articular Set Angle) has been linked to bunion formation(LaPorta et al., 1974b) and might result in Neandertals having a greater hallux valgus angle than seen in modern humans, despite being unshod.

The recently discovered remains of *Homo antecessor* are said to be the last common ancestor of modern humans and Neandertals.(Lorenzo et al., 1999) Only a few metatarsal fragments have been found, none of them being a 1st metatarsal. The proximal phalanges of the hallux do not differ greatly from modern humans except for the bases, which are reported to be very round.

The evolutionary development of the foot hints at difference rates of development between the forefoot and rearfoot as well as medial and lateral differences. Variation between male and female foot bones in different primates and evolutionary species have been noted, but investigation of the differences has never taken place.

Forensic studies have given greater consideration to gender differences in order to enhance identification of unknown subjects. Two studies considered the rearfoot bones of the talus and calcaneum(Steele, 1976;Singh and Singh, 1973) and two studies have considered metatarsal length for the purpose of estimating stature.(Smith, 1997;Byers et al., 1989) The differences found between genders in these studies were not described in terms of the impact they would make on the function of the foot.

In forensic science, the measurement of foot bones is undertaken with a view to identification of the foot size and thus to estimate height. Byers *et al* (1989) found good correlations between the lengths of the metatarsals and stature, with differences being noted between males and females.(Byers et al., 1989) Steele (1976) observed sexual dimorphism in the talus and calcaneum (n = 61) with the males being significantly larger, but found that the overlap between individual measurements was so great that a combination of measurements was required in order to predict sex accurately. For the talus, the use of three discriminant functions gave an accuracy that ranged from 83-88%. Smith (1997) found a similar level of accuracy of discrimination for sex and population in a study on 160 metatarsals and phalanges.(Smith, 1997)

The forensic studies have tended to use the measurements of foot bone lengths and widths that, in general, have been based upon the descriptions by Martin and Saller (1957).(Martin and Saller, 1957) These have also been used in anthropology alongside the detailed methods developed by Lisowski (1967), which were based upon the earlier measurements of Martin and Saller.(Lisowski, 1967);(Lisowski et al., 1974) Lisowski detailed the use of standardised reference planes when taking measurements using callipers and protractor. This "hands on" method has changed little over the last 35 years. The use of the standard reference planes allowed for the bone to be positioned relative to the body planes and this in turn allowed for comparison between species and between studies. The reference planes are only described for the larger bones. Standardised positions for the smaller bones such as the navicular and cuboid are based upon the morphology of the bone rather than with reference to a body plane.(Kidd et al., 1996)

Although simple techniques such as direct measurement with callipers and protractor are still used, technology is beginning to be developed that allows for more accurate measurement. Digital photographs have been introduced but taking measurements from these is subject to error from the original camera angle and the ability to locate reference points on the photographs. Computerised systems such as "Microscribe" allow for more accurate measurement whereby a computer generated model is created through visual location of reference points and the linear and angular measurements are calculated from the 3D data sets. "Microscribe" however, is limited by its graphical representation of the bone. If further or repeat measurements are required, then the investigator needs to return to the original bones. In most cases, the method of measurement is limited by the ability to take the technology to the bone collections since most are, quite rightly, cosseted by the various museums.

With the introduction of new 3D measuring systems, the method of taking the individual measurements needs to be re-considered. For example, when measuring the talus, determining the angle between the neck and body of the talus has been found to be a useful aid when distinguishing between different species (Kidd et al., 1996). Lisowski described the measurement of this angle (talar neck-body angle) as being made by the intersection of the sagittal talar plane and the median talar neck plane. However, the measurements were made with callipers and by only connecting two points can only create a line and not a plane. Lisowski's method in effect creates a line that, when superimposed on the trochlear surface, would divide the talar body into left and right halves and a line superimposed on the talar neck that appears to separate it into left and right halves. The angle between these lines, if they were positioned in a horizontal plane, would form the talar neck-body angle. However, such an angle may not really describe the position of the body to the neck. The reason for this is that it is unlikely that the dividing line on the body would not be in the horizontal plane given the curvature of the trochlear surface that runs from posterior-inferior to anterior-superior. The talar neck is positioned from posterior-superior to anterior-inferior so a superimposed line would be angled away from the horizontal plane. A better representation of the position of the talar neck to body angle would be though the creation of planes that divide the structure into left and right halves and then find the angle between the two planes. With new technology, it is possible to return to the original descriptions by Lisowski and create reference planes with the use of multiple reference points - a line is created between two co-ordinates, a plane is formed between three co-ordinates. The angle between the two planes is calculated as the angle between two lines, one in each plane, where the lines area at right angles to the intersection of the two planes. To date, the true angle between bony surfaces has not been calculated in anthropometric or forensic studies due to the limitation of using 2-dimensional methods.

3.2 Aim

It would appear from the literature that although there are many theories on the cause of HAV, none of these explain the increased prevalence in women. The primary feature of an adducted metatarsal may be related to early evolutionary development of the foot but whether the changes have led to differences in the male or female foot is not known. The aim of this study is to apply a new technique to consider the sexual dimorphism of the bones in the medial column of modern feet and to review the differences with reference to the potential to develop hallux abductovalgus deformity.

This study introduces a new method for measuring foot bones and considers whether the bones differ in size and shape between the sexes in such a way that the gender of an individual can be identified.

3.3 Method

The Natural History Museum, London granted permission to access the Spitalfields Collection. This collection consists of around 300 Victorian British skeletons that were housed at the museum following demolition of a graveyard during the rebuilding of the Spitalfields market site. The collection mainly consists of the French Protestants known as the Huguenots, who settled in the Spitalfields area at the end of the 17th century after escaping France when Louis XIV issued the Revocation of the Edicts of Nantes in 1685. A large proportion of the Huguenots were silk weavers who continued their trade in the area and enhanced the silk industry in England. Many of the Huguenots became relatively wealthy and on their death were buried in the parish church yard. Because most of the graves had headstones, the name, sex, date of birth and death are known for most of the skeletons.

At the Natural History Museum, each skeleton was housed in up to 2 boxes. The bones were in variable condition, some greatly affected by a fire that had occurred in the crypt of the church prior to excavation.

A list of the skeletons was provided by the museum and working from the list, the talus, navicular, medial cuneiform and 1st metatarsal bones were taken from fully ossified subjects that were in good condition and of known age and sex, until 50 male and 50 female skeletons were selected. Only adult skeletons were included so that all secondary centres of ossification were fused.

Each bone was scanned using a hand-helded, Polhemus 3D laser scanner to create a digital image. The bone was mounted on a black stand in a darkened room. The laser scanner repeatedly swept the bone in all planes until the reflected light had formed a suitable image of all sides of the bone, as shown on a computer screen. The images were analysed using the "Cloud" software system (http://www.medphys.ucl.ac.uk/research/mgi/vis-lasr.htm).(Linney et al., 1997) This Optical Scan Viewer System allows the 3D image to be rotated so that any surface can be viewed. Markers can be added interactively to the bone surface and the software will then provide measurements. For example, linear distances between surface markers can be measured, lines between two points can be created and angles between lines found. Planes through sets of points can be formed and measurement of angles between planes can be made. Surface reference points can be located both visually and with the use of contour lines that run horizontally and vertically revealing any change in direction of the bony surface.

The measurements for each bone were selected from published anthropometric.{(Lisowski et al., 1974;Lisowski, 1967;Kidd et al., 1996)

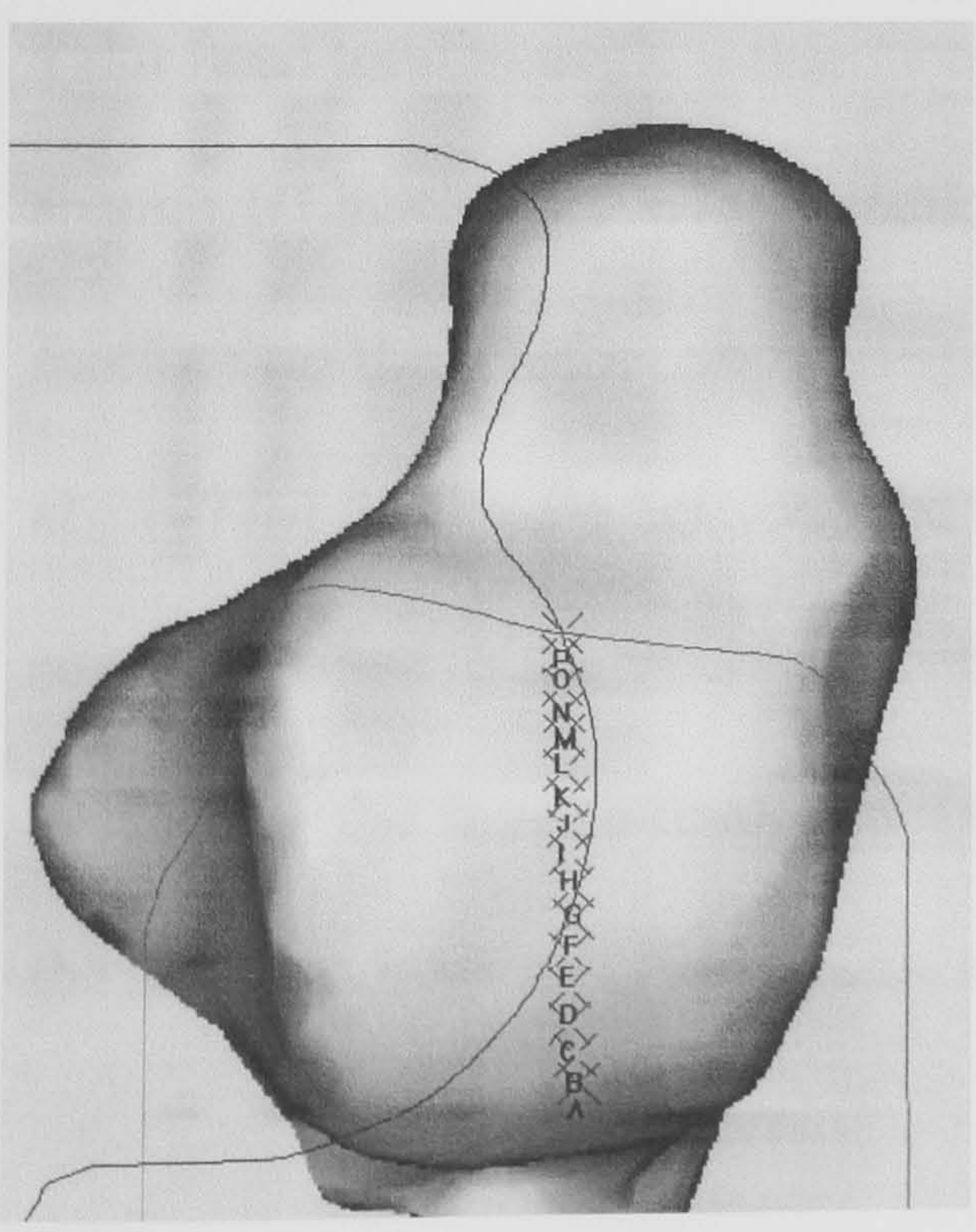
3.31 The TALUS

When placing marker points, the 3D image of the talus was viewed from standardised positions unless otherwise stated. When viewing the anterior or posterior surfaces, the talar head was positioned so that it was level with the posterior tubercle as if it were resting on a horizontal surface. The dome of the trochlear was kept horizontal and the medial surface was not visible. For lateral views, the opposite side of the talar dome would just be evident around the whole curvature of the surface.

Measurements required:

Talar neck-body angle – this measurement distinguishes the human talus from other species such as the primates. The angle between the longitudinal bisection of trochlear surface (median sagittal talar plane) and the longitudinal bisection of neck of talus (median talar neck plane) was measured. This angle has been linked to adduction of the 1st metatarsal.(Kidd et al., 1996)

The original description of this measurement does not define the markers used to create the bisection but superimposes a line to bisect the body and neck of the talus into left and right halves.

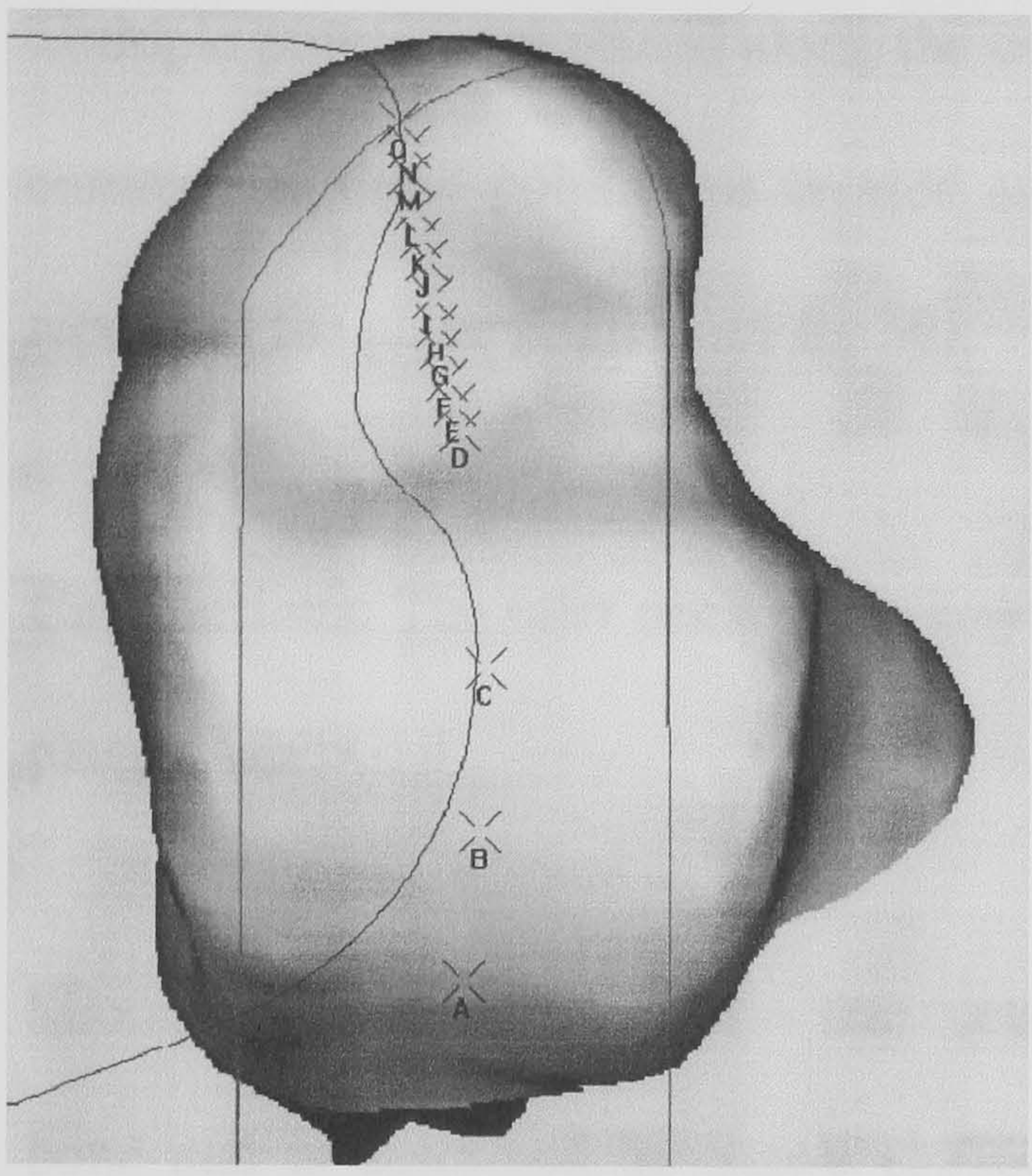


To create the bisections in this study, multiple points were first placed along the midline of the body of the talus. The Cloud software can provide a plane that will form the "best fit" to the points using a least squares regression function. The system then applies points on the plane that are closest to the originally chosen markers (see figure 28).

Figure 28. Dorsal view of talus with multiple points added.

All but three points were then removed and these represented the plane (ABC) (see fig 29).

Figure 29. Showing the plane ABC and multiple points added placed on the talar neck to create the neck bisection plane.



The process was repeated along the midline of the neck of the talus and the representative plane created with three points being chosen on that plane. (see fig 29). The angle between the two planes was recorded.

Calculation: the talar neck angle was the angle formed between the planes ABC:DEF

Talar head torsion angle – this measurement distinguishes the human talus from other species.{(Lisowski, 1967) Functionally, the angle is related to the position of the forefoot on the rearfoot and changes during the early stages of development.(Root et al., 1977b) The angle between the trochlea–head plane (created by points joining the superior points of the trochlear margins to the talar head) and the longitudinal axis (median axis) of the head has been described.(Kidd et al., 1996)

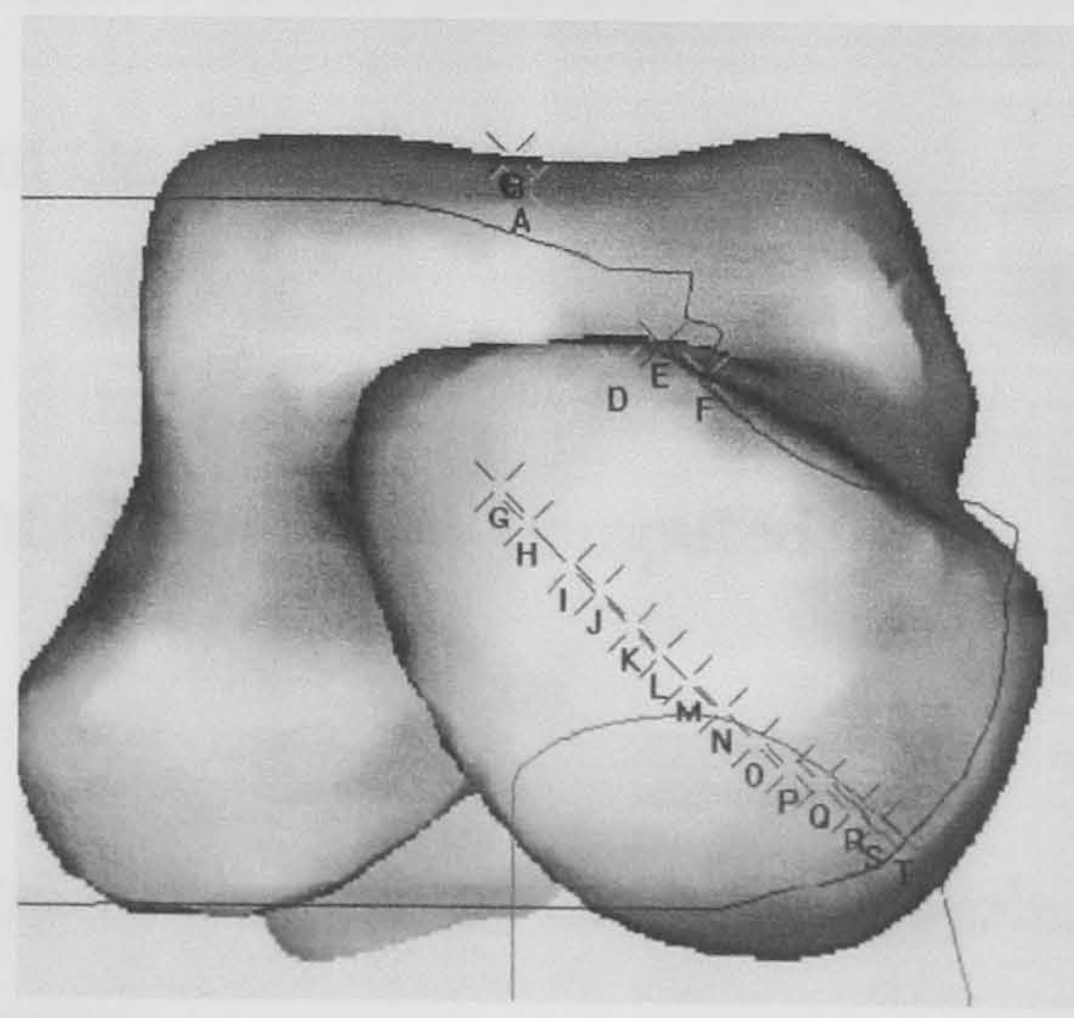


Figure 30. Anterior view of talus showing the multiple points used to create the talar head bisection.

In this study, the plane ABC was used to represent the vertical bisection of the talus and was used rather than the horizontal bisection suggested by Lisowski (90^0 – this angle = Lisowski's angle)

Multiple points were placed along the centre of the talar head facet. The plane that is common to these points was created and then all but three points were removed to represent the plane (GHI) (see fig 30).

Calculations: The talar neck angle was measured from the angle created between the planes ABC:GHI.

Maximum functional length – this measurement is used to compare the size of the bone and is described by Steele (1976) based on Martin and Saller (1957).(Steele, 1976) The length is usually measured from the sulcus for the flexor hallucis longus tendon on the posterior surface (at the point of maximum curve) to the most anterior point on the articular surface for the navicular (at the maximum curvature) using callipers.

In this study the maximum curve of the talar head facet was located with the bone viewed superiorly and then rechecked with the bone viewed anteriorly (J) using the superimposed contour lines. The maximum vertical curve at the posterior edge of the trochlear surface was used with the bone viewed from the posterior aspect (K).

Calculation: The straight-line distance between points J and K was computed.

Maximum width – this measurement is used to compare the size of the bone (Steele, 1976). The maximum projection lines both laterally and medially perpendicular to the sagittal plane were created. The most prominent point on the lateral, fibular facet was located (L). The point on the medial surface of the talus was located directly perpendicular to L (M).

Calculation: The straight-line distance between points L and M was computed.

Ratio of the maximum talar head long dimension to the maximum talar head short dimension – this functional measurement was described by Kidd *et al* (1996) who referenced Lisowski (1967). Kidd reported the index created might indicate the degree and direction of talonavicular movement. If the movement was excessive in a medial-lateral direction along the length of the facet, this might lead to adduction of the navicular and then adduction of the 1st ray.

It may be supposed that a higher ratio or greater value of the length (from medial to lateral) compared to width (dorsal to plantar) may indicate that the joint surface is oval in shape and therefore more movement will occur in the medial - lateral direction. A value closer to 1 would indicate that the joint surface is round and therefore movement is equal in each direction.

The dorsomedial edge of the talar head facet was identified where it joins the neck of the talus (O). From a dorsal view, the point was located where the vertical projection shows the surface to be flat but then curves sharply away onto the dorsal surface; the horizontal line showed a flat area just as the curve of the head finished (see figure 31).

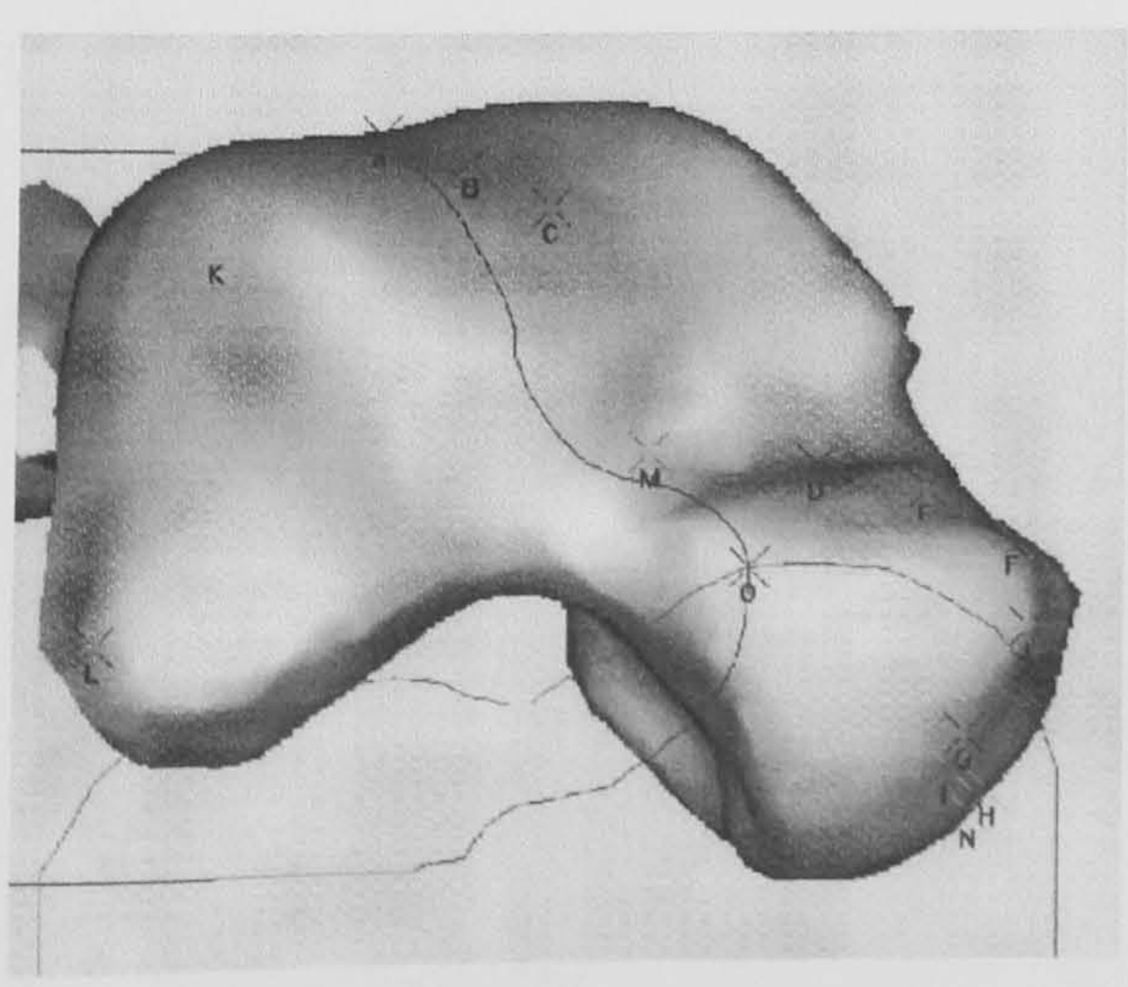


Figure 31. Anterior-lateral view of the talus

On a medial view, the point was marked where the talar head facet joins the horizontal. The bone was then tilted so that this marker could be moved into the centre of the facet at that level. The contour lines showed the facet becoming flat where the head rested on the sustentaculum tali. This point was marked (P).

The centre of the articular facet was identified (N) and the widest points of the facet to the perpendicular to the central marker on the dorsal and plantar edge were found (Q and R).

Calculations: The straight-line values of O-P / Q-R was calculated to indicate the shape of the joint surface.

The functional angle of the talar head facet - this angle was calculated using the equation of Latimer and Lovejoy (1989). The radius of the curve through points O,P and N was calculated and the chord length (OP) measured.

Functional angle of curve $\sigma = 2\sin^{-1}$ (Chord length / 2 x Radius of curve)

Proximal articular set angle (PASA) – this is a functional measurement originally described with reference to the 1st metatarsal head to describe the position of the joint surface compared to the longitudinal axis of the bone (LaPorta et al., 1974). Here the method was applied to the talar head. The angle formed between the talar neck plane bisection (DEF) and the plane bisection of the talar head (see figure 32). This angle will influence the alignment of the forefoot.

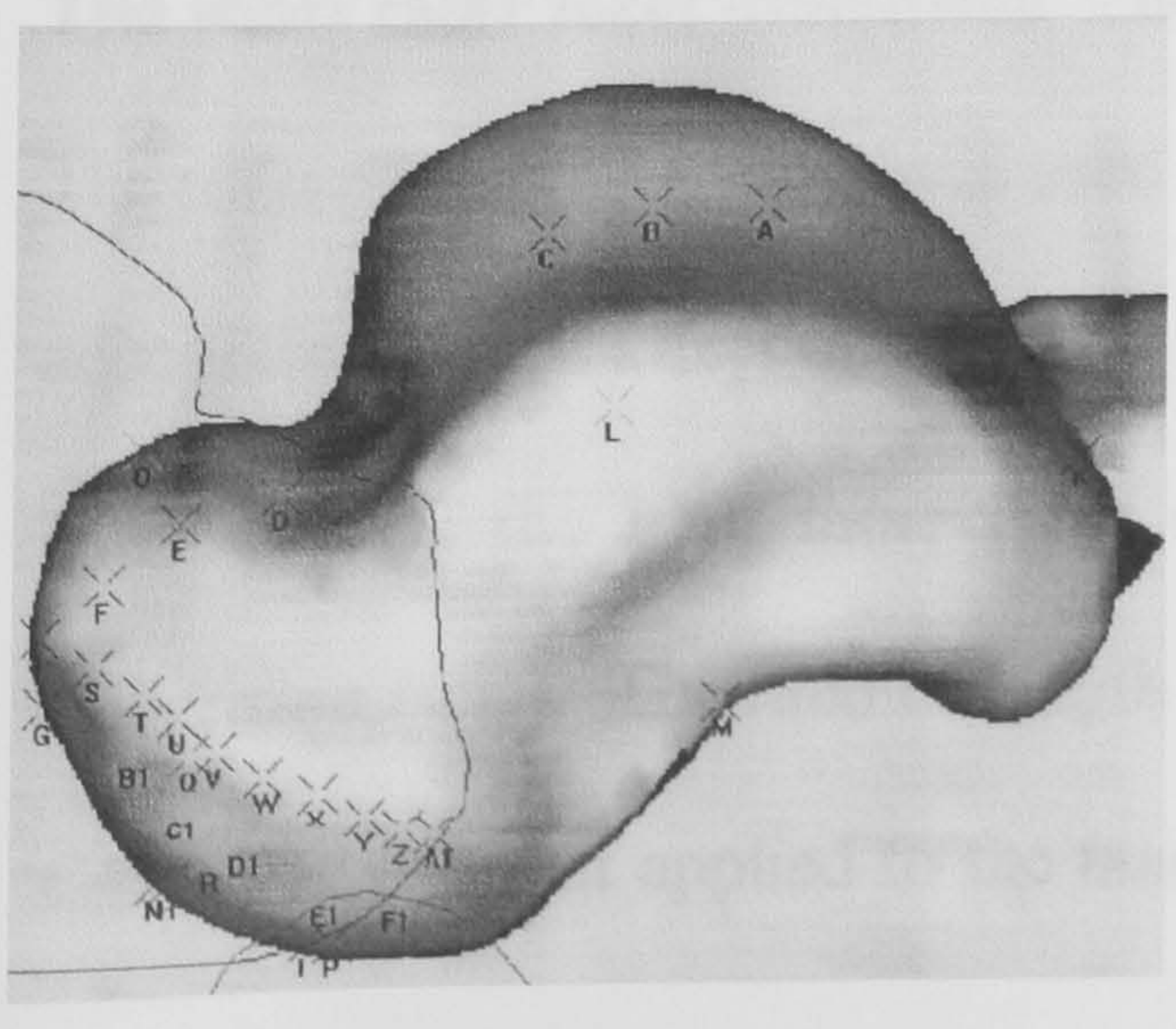


Figure 32. Medial view of talus showing multiple points placed around the edge of the talar head facet to create the plane of the PASA.

Multiple points were added around the edge of the talar head facet on the dorsal and plantar edges and a plane created. Three points were selected to represent the plane (S,T,U)

Calculation: the angle DEF:STU formed the PASA measurement.

A second measurement was compared to this. The lines LM across the body of the talus and the line MN will join the medial side of the talus to the centre of the talar head. Simple trigonometry allowed the angle between LM and MN to be calculated. Larger angles would be associated with a more medially placed talar head.

3.32 The NAVICULAR

When measuring this bone from the anterior or posterior views, the plantar surface was kept in the horizontal plane. On the anterior view, the non-articular "shelf" under the lateral cuneiform facet was just evident.

Measurements required:

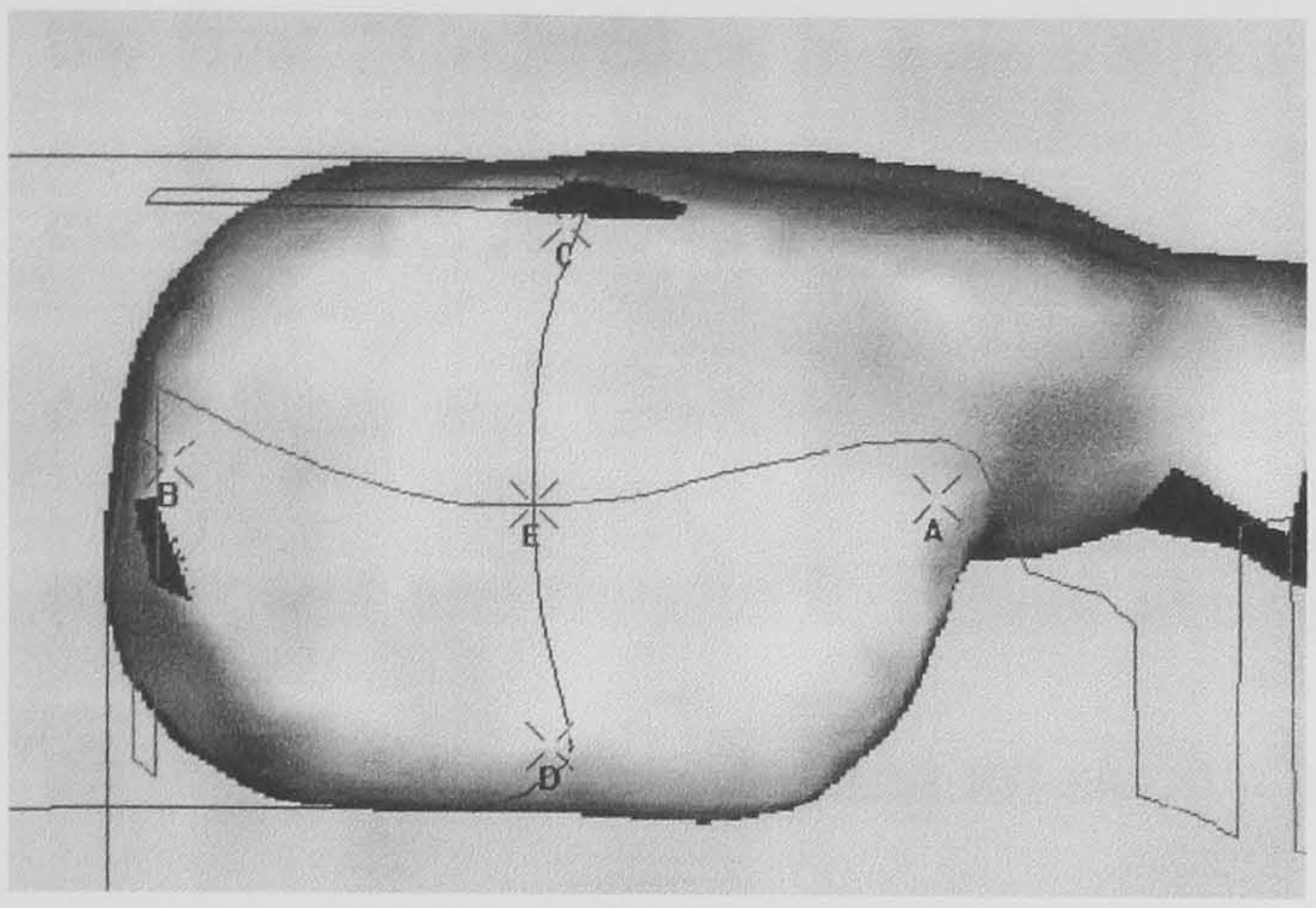
The long talar facet dimension – the maximum dimension of the talar facet was described by Kidd and referenced to Lisowski (Kidd et al., 1996).

The short talar facet dimension - the minimum talar facet dimension.

The ratio of length to width was used to access for differences between the bones after accounting for the affect of size.

The ratio of the long talar facet dimension (AB) / the short talar head facet dimension (CD). The ratio of length to width (described by Kidd 1999) was used in a similar way to that applied to the talar head. Excessive length of the long dimension may indicate greater medial / lateral movement of the bone suggesting that movement may be possible in a direction that leads to an adducted 1st ray.

Figure 33. View of talar head facet on the navicular



Point A: The medial edge of the talar facet.

This point was found where the vertical projection shows the surface to be at its maximum and the horizontal projection showed the upward curve towards the facet and then the dip into the facet.

Point B: The lateral edge of the talar facet.

This point was found where the vertical projection shows the surface to be at its maximum and the horizontal projection showed the upward curve towards the facet and the dip into the facet.

Point C: The central plantar edge of the talar facet.

This point was found where the vertical projection shows the surface to be at its maximum before curving behind the bone and the horizontal projection showed the bone to curve forward.

Point D: The central dorsal edge of the talar facet.

This point was found where the vertical projection showed the surface to be at its maximum before curving behind the bone and the horizontal projection showed the bone to curve forward.

Calculations: The value of the straight-line distances A-B/C-D was calculated to represent the shape of the articular surface (see figure 33).

Point E: The centre of the articular facet was found at the point of maximum vertical and horizontal curves.

Functional angle of curve of the talar facet - this was measured along the midline of the facet. Undertaken in a similar way to that described for the talar head, a best-fit curve though AEB was applied and the functional angle calculated using the formula of Latimer and Lovejoy. An increased angle may be relate to a greater range of movement and thus an increased ability of the navicular to move medially / laterally on the talus, thus suggesting an ability to adduct the 1st ray.

The ratio of the medial bone width / lateral bone width was described by Kidd (1999) and is reported to give an indication of the wedged shape of the bone.

With the anterior surface of the bone facing, the most medial edge of the articular facet for the medial cuneiform and the most lateral edge of the articular facet for the lateral cuneiform, were marked (points F and G).

Point F: This point was located at the medial edge of the medial cuneiform facet. The horizontal projection showed a flat section before the curve starts over the cuneiform facets. The vertical projection showed the maximum dorsal-plantar curve. When viewed from the anterior view, point F was level with point A.

Point G: This point was located on the lateral edge of the lateral facet and showed as a peak in the horizontal and vertical curves. Point G was opposite point B.

Calculations: The medial width was measured between the medial marks A-F, the lateral width was measured between B-G and a value of A-F/B-G calculated. A value of 1 would indicate than the medial and lateral edges of the bone are equal. A value of less than 1 indicates that the medial border is reduced in width and this would lead to the medial cuneiform being more adducted in relation to the lateral cuneiform and in turn would lead to an adducted 1st metatarsal.

Figure 34. Dorsal view of the navicular showing the angle of the medial cuneiform facet

Medial cuneiform facet angle (see figure 34) – angle formed between the tangential line across the intermediate cuneiform facet and the tangential line across the medial cuneiform facet. This measurement was described in the capitate bone for the hand using line bisections (Niewoehner et al., 1997). A large angle will result in the adduction of the medial cuneiform and 1st metatarsal.

Two planes were created representing the plane of the medial facet and a plane that combined the intermediate and lateral cuneiform facets.

Point H: This was located to the ridge that divided the medial and intermediate facets on the dorsal edge of the anterior facet. The peak of the horizontal and vertical projection was marked.

Point I: This was located to the ridge that divided the medial and intermediate facets on the plantar edge of the anterior facet.

Calculations: Using the points that identified the medial and lateral edges of the anterior face (F and G), the angle between the planes FHI and GHI was found (see figure 35).

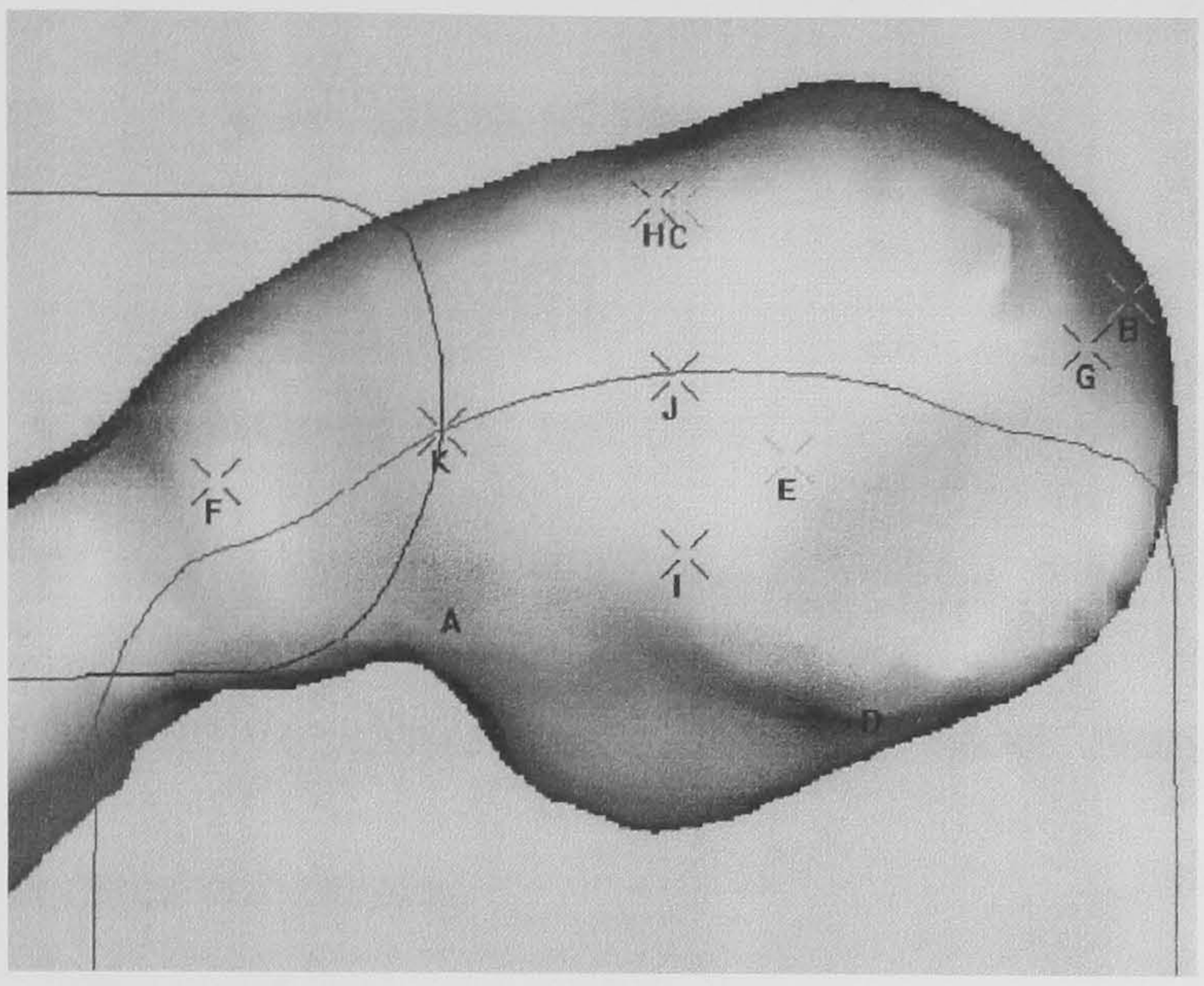


Figure 35. Anterior view of the navicular showing points creating the planes FHI and GHI.

Functional angle of curve for medial cuneiform facet – this measurement was taken along the midline of the facet (see figure 36). It was found in a similar way to the functional curve of the talar head. With the dorsal surface of the navicular being viewed, the "best fit" curve to the joint surface was applied and the calculation for the functional angle made using the formula above.

An increased functional angle may be related to increased movement in the direction of abduction / adduction of the 1st ray.

The midpoint of H-I was marked (J). The midpoint of J-F was found (K). When viewed from the medial side, JKL formed a straight line.

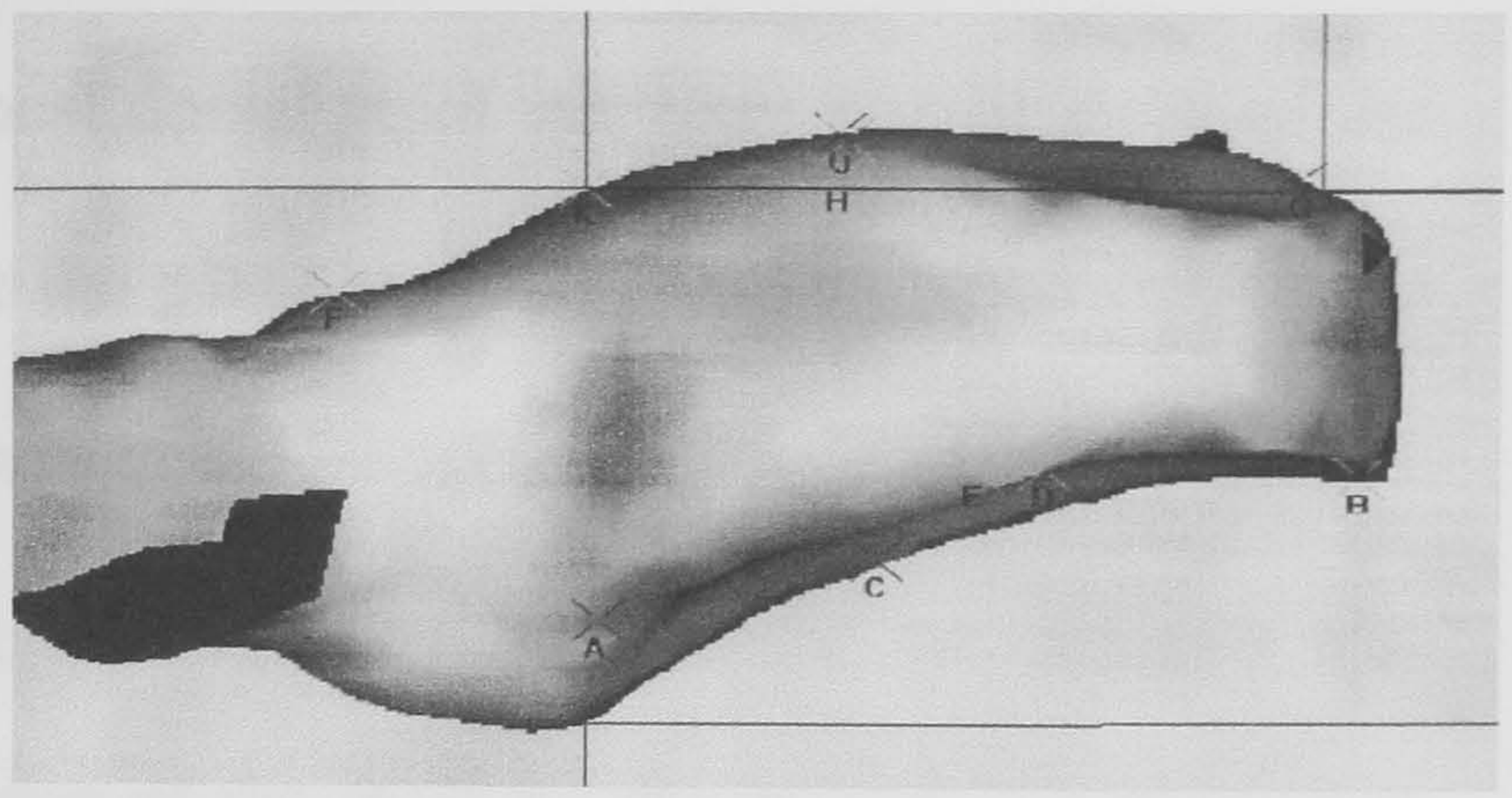


Figure 36. Plantar view of navicular showing the curvature of the 1st ray facet

Calculation: The radius of the curve through FJK was found. The distance between F and J formed the chord. The functional angle could then be calculated. A subjective description of the facet was given using the groups: convex, flat, concavoconvex.

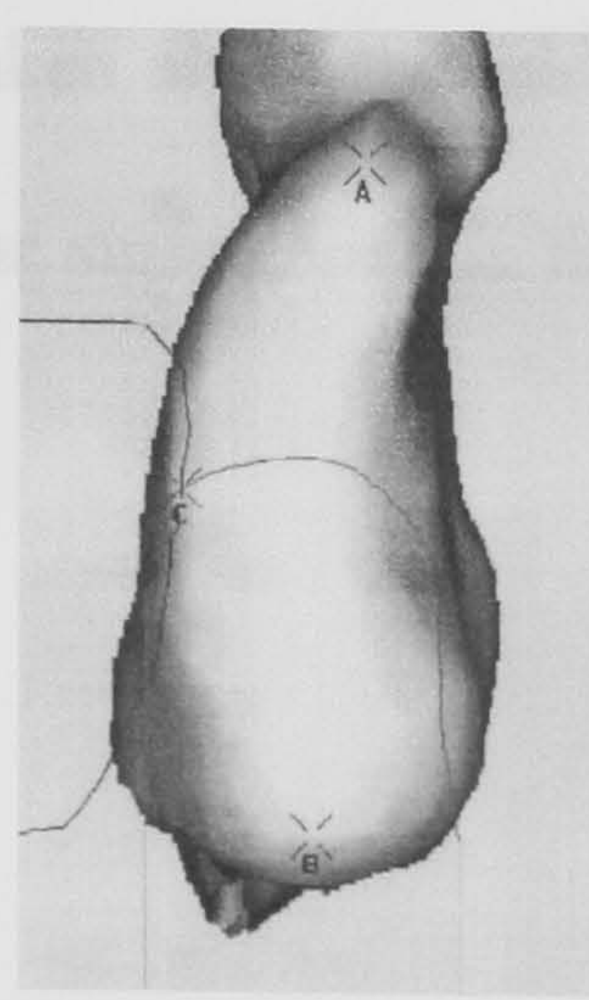
3.33 The MEDIAL CUNEIFORM

When measuring the cuneiform, the anterior and posterior surfaces were viewed with the medial surface of the bone being placed on the horizontal plane.

Measurements required:

Distal joint angle – this measurement is of the angle formed from a line joining the medial and lateral edges of the distal facet to the line joining the proximal and distal edges of the lateral facet for the intermediate cuneiform (Schultz, 1930). Schultz described the line-bisections used to create the angle. In the present study, the angle between the planes forming each surface were measured.

Figure 37. The anterior surface of the medial cuneiform showing points ABC.



With the anterior surface facing, the most dorsal point and most plantar point of the facet were marked A and B. To create the plane, a third point (C) was found at the medial surface approximately at the centre of the bone (see figure 37).

With the lateral-posterior surface facing, the apex of the facet for the navicular was marked (D) and the plantar-proximal edge of the facet for the second cuneiform was found (E). To create the plane, the third point at the dorsal-anterior edge of the facet for the second cuneiform was marked (F) (see figure 38).

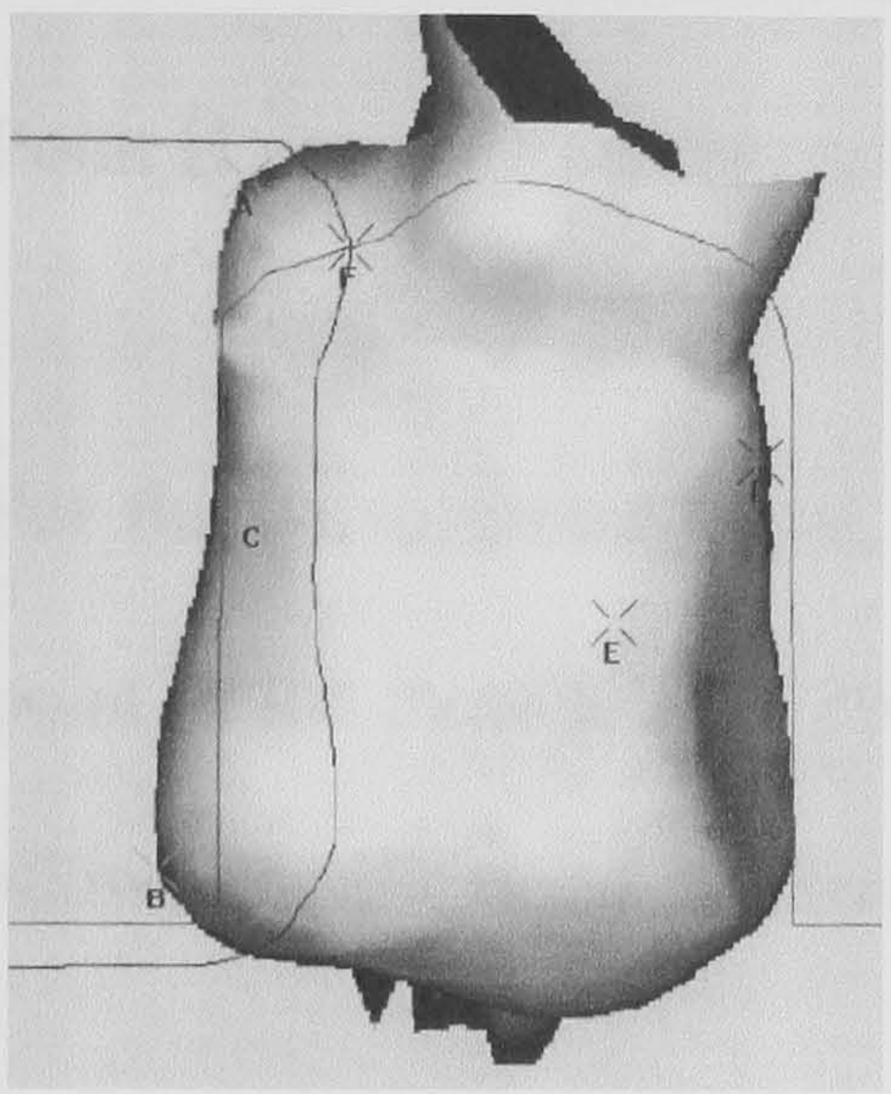
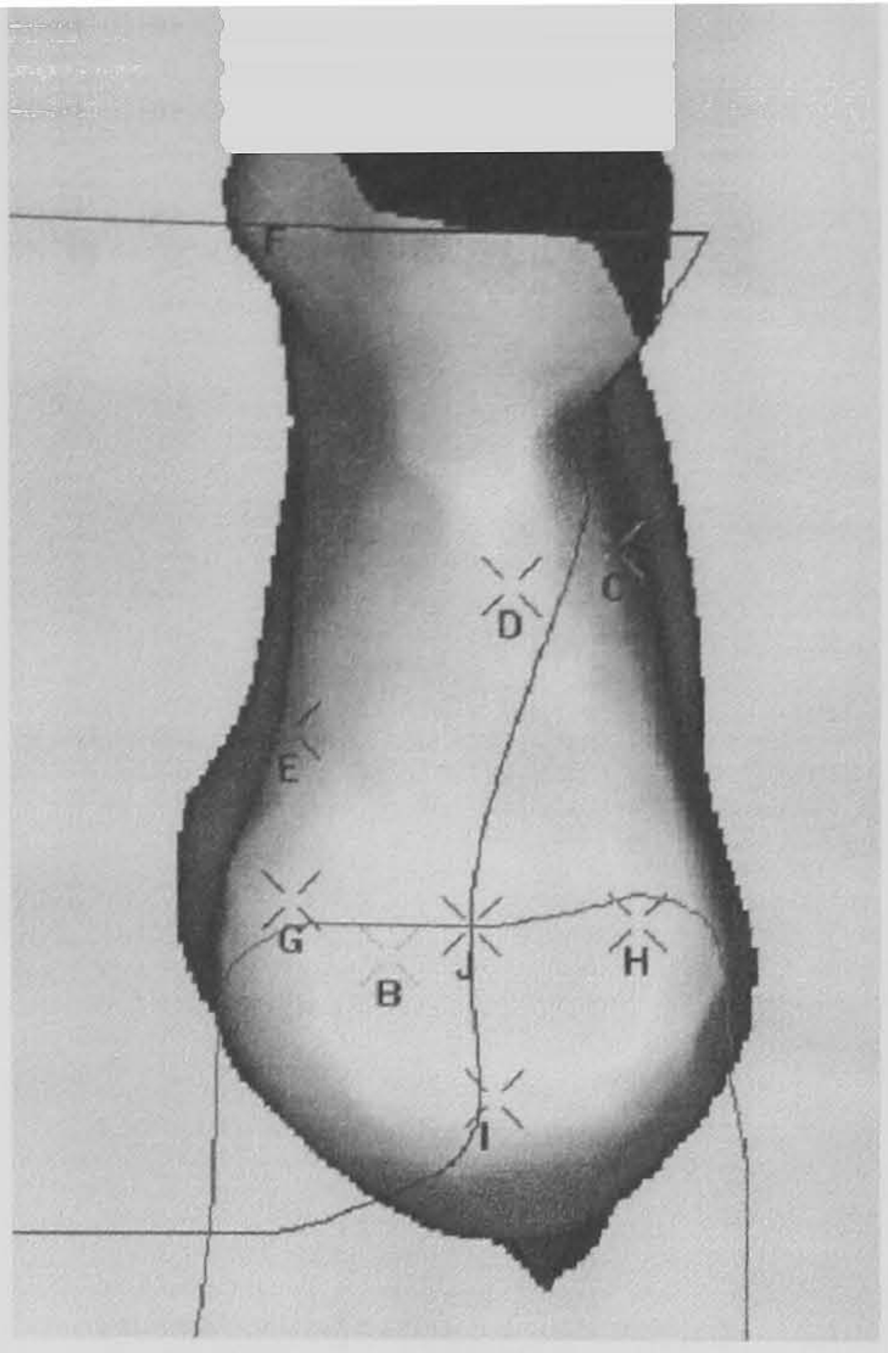


Figure 38. Lateral surface of the medial cuneiform showing points DEF.

Calculation:

The angle between the planes ABC and DEF were found and represented the angle measured by Schultz. A second measurement ABC:ABI was tested for improved accuracy.

The radius of curve of the navicular facet – this measurement described the radius of the "best fit" curve applied to the posterior facet. It was taken along the midline from the dorsal apex of the facet to the midpoint of the plantar surface of the facet. The curve from medial to lateral was also calculated.



For the medial-lateral curve, the points G,H,I were created. When the bone is present in an articulated foot, this curve allows abduction / adduction of the cuneiform on the navicular.

Figure 39. Posterior view of medial cuneiform

Point G was the most medial edge of the bone. Point I was in the centre of the bone. Point H was the most lateral edge of the bone.

For the dorsoplantar curve, the points D,I and J were found where Point J was the point at the most plantar point of the bone. When the bone is articulated, this curve allows dorsiflexion / plantarflexion of the cuneiform.

Calculations: The radius of the curves DIJ and GHI were found and the chord lengths DJ and GH were measured (see fig 39) and from these the functional angle of curve of the navicular facet could be found.

The radius of the curve of the metatarsal facet – the cuneiform was placed with anterior surface facing, the radius of the curvature across the centre of the metatarsal facet running from lateral to medial was calculated along with the chord length.

The points C, L and K were found. Point C corresponded to the same point above. Point K represented the most lateral point of the bone and K was found at the centre of the bone, in line with C and K (see figure 40).

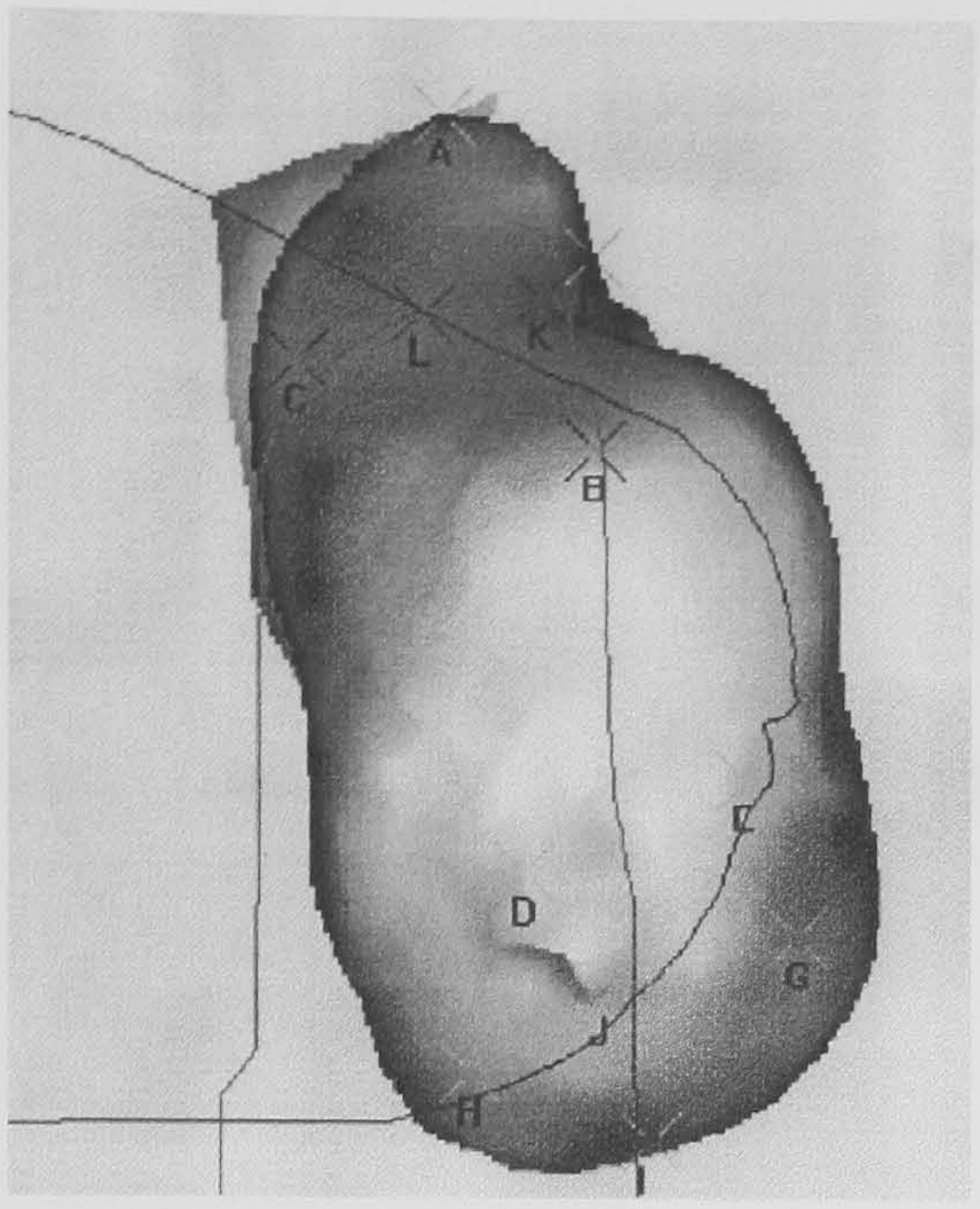


Figure 40. Plantar view of medial cuneiform showing curve of anterior surface.

Calculation:

The radius of curve CLK and the chord length CK and the functional angle of curve of the metatarsal facet were calculated which is important with respect to adduction of the metatarsal.

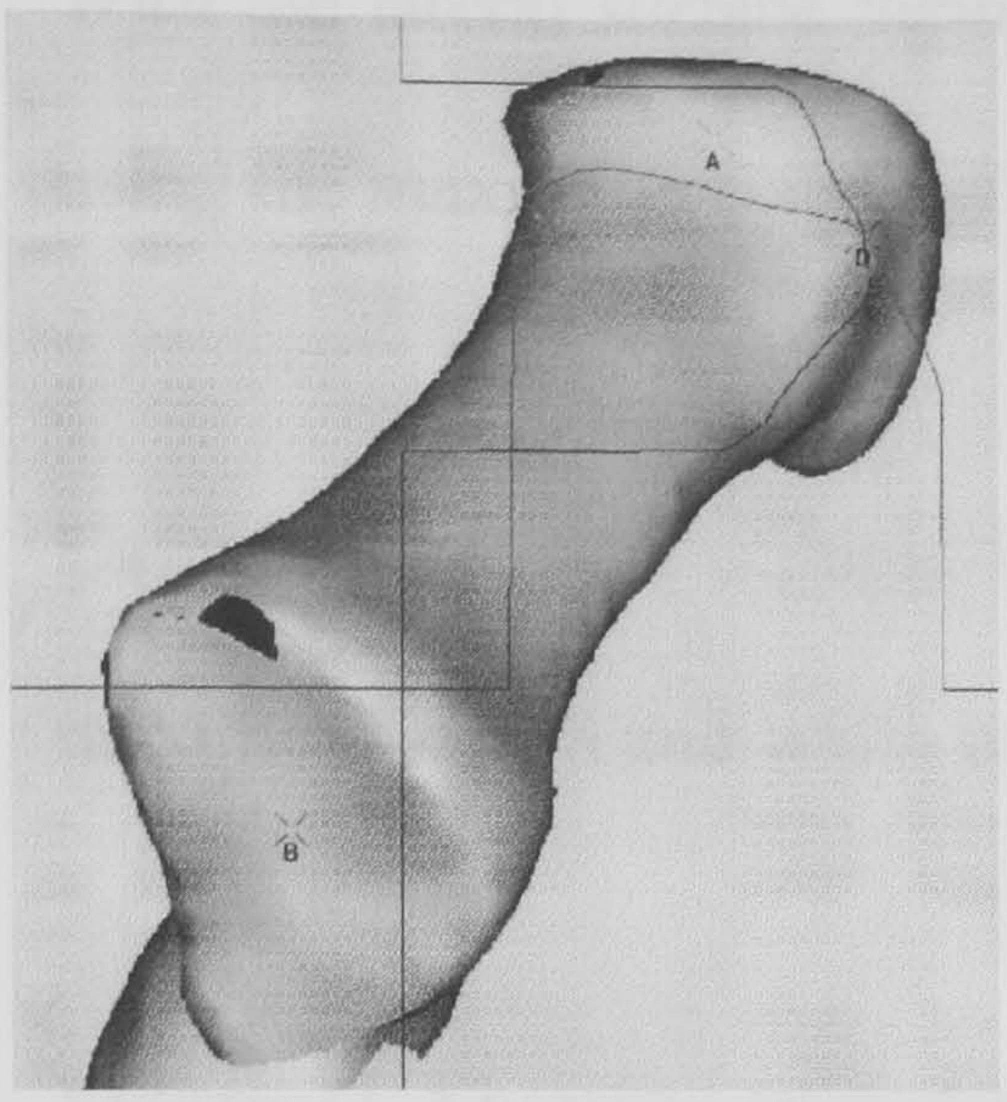
3.34 The 1ST METATARSAL

When the metatarsal was measured, it was positioned so that the plantar projection on the basal facet was pointing directly plantar. When the anterior surface (metatarsal head) was viewed, the crista was placed plantarly and the metatarsal base could be seen equally around the edge of the metatarsal head. On the lateral views, the base of the metatarsal appeared flat and was perpendicular to the viewing screen.

Measurements required:

Metatarsal length – this measurement is from the apex of the capitulum (head) to the midpoint of the articular surface of the base parallel to the longitudinal axis of the bone and **Metatarsal head width** – this measurement is the width between the medial and lateral epicondyles (Smith, 1997; Byers et al., 1989).

Figure 41. Dorsomedial view of 1st metatarsal showing points A and B.



Point A: The central point of the metatarsal head facet.

With the metatarsal head facing, the point was found by locating the centre of the horizontal and vertical curves of the facet.

Point B: The central point of the cuneiform facet.

With the base of the bone facing, this point was found by locating the centre of the horizontal and vertical curves of the facet.

Point C: The medial epicondyle

With the medial surface facing, the highest point of the medial epicondyle was found using the maximum points of curvature of the horizontal and vertical projections.

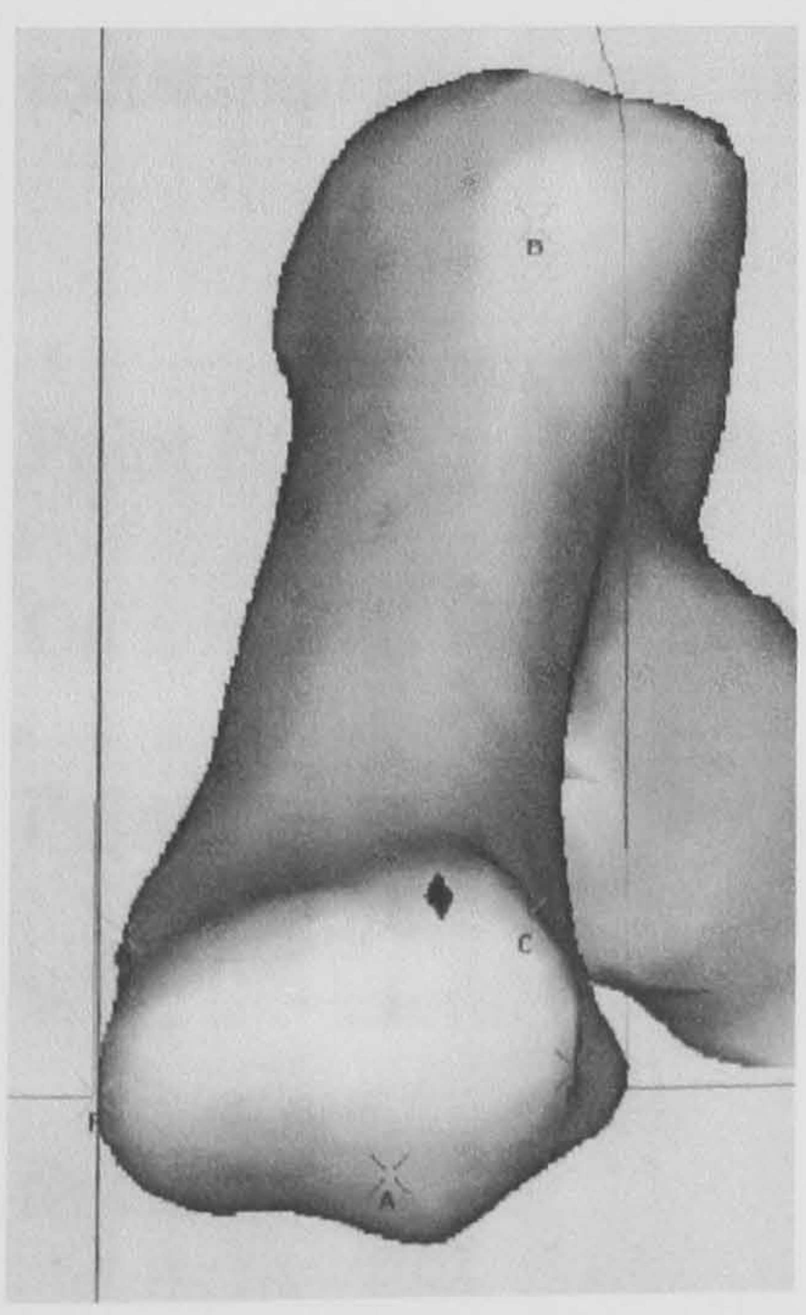


Figure 42. Anterior -dorsal view of 1st metatarsal

Point D: The lateral epicondyle

With the lateral surface facing, the highest point of the lateral epicondyle was found using the maximum points of curvature of the horizontal and vertical projections.

Calculations: The straight-line distances between A-B and C-D represented the maximum length and width respectively (see figures 41 & 42).

Figure 43. Showing curvature of metatarsal head

Image removed due to third party copyright

The radius of the curve of the metatarsal head – this measurement was described when calculating the functional angle of a joint (Latimer and Lovejoy, 1989).

Using points A (as above) with points E and F, the curve across the centre of the metatarsal head was calculated (see figure 43).

Point E: The mid-point of the articular facet medially.

On a medial view, the midpoint of the horizontal and vertical curves was found.

Point F: The mid-point of the articular facet laterally.

With the lateral surface facing, the midpoint of the horizontal and vertical curves was found.

Points E and F were placed on the same level in the transverse plane.

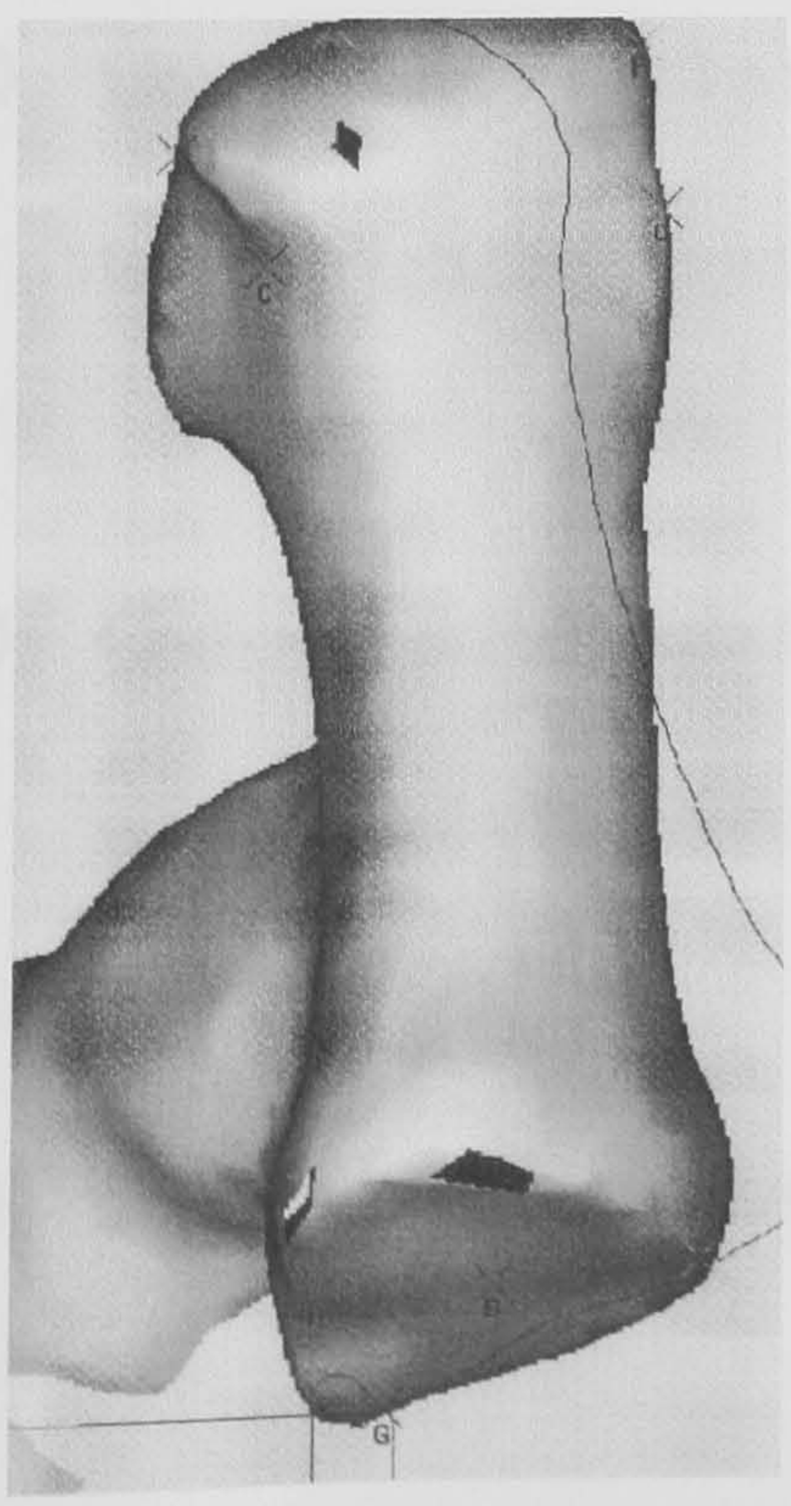
Calculation: The functional angle through curve AEF were found which related to abduction on the hallux on the metatarsal head.

The proximal articular set angle (PASA) – is a functional measurement (LaPorta et al., 1974) that describes the position of the metatarsal head articular facet relative to the bisection of the metatarsal shaft. With the metatarsal head facing, the medial and lateral edges of the facet were joined across the midline of the joint surface. The bone was then viewed from the dorsal direction, the shaft was bisected longitudinally with the plane ABG. The angle between the shaft and the head was measured.

The PASA represents the position of the metatarsal head articular facet relative to the bisection of the metatarsal shaft. A laterally deviated head is related to the development of hallux valgus.

Calculation: angle between the line EF and plane ABG (see figure 44).

Tarsometatarsal joint angle – this angle is formed between the bisection of the medial and lateral sides of the 1st metatarsal base and the longitudinal bisection of the bone. This angle would indicate the alignment of the 1st metatarsal on the cuneiform, an increased angle being associated with adduction of the metatarsal.



On a view of the base of the metatarsal, the plantar edge of the metatarsal plantar projection was marked (G). The widest point of the base was marked on the edge of the facet both medially (H) and laterally (I).

Figure 44. Showing angle of base of 1st metatarsal showing points G,H and I.

Calculation

The angle between the planes ABG and GHI was be found.

Repeatability and validity

Initial pilot studies suggested that the repeatability of each measurement was good. To improve acuracy, each measurment was taken five times and the mean value included in further analysis of the data. The validity of the scanning technique was tested by comparing the measurements with calliper measurements. Pilot study data are presented in Appendix III.

3.4 Data Analysis

◊ In order to chose between the application of parametric or non-parametric tests to continuous data, all measurements were tested for normality of distribution using a 1 sample Kolmogorov-Smirnov test.

◊ Comparison of left to right sides for each bone were made using either a paired t-test or Sign test depending upon the normality of the measurement distribution.

◊ Comparison of male to female bones was made using a t-test when the distribution was normal or a Mann Whitney test as the non-parametric alternative.

◊ Comparison of nominal data was made using a Chi squared test.

◊ To investigate the usefulness of each measurement in identifying gender, stepwise logistic regression was applied and probability plots used to display differences visually.

3.5 Results

A total of 107 subjects were measured. This included 53 males and 54 females. The numbers of each bone used is given in table 7. The data was analysed using SPSS® for Windows.

Table 7. Number of foot bones analysed

	Males	Females
Tali	52	54
Naviculae	49	53
Cuneiforms	52	54
Metatarsals	53	52

The distributions for each measurement were tested using a 1 sample Kolmogorov-Smirnov test. All measurements were normally distributed ($p \geq 0.06$) allowing for parametric tests to be applied.

The use of indices (ratios) in anthroplogy has been subject to some criticism. Indices are often used to account for the effects of size and it has been questioned whether it is appropriate to use them for this purpose and when the ratios are created, whether any change in distribution of the data is assessed for before statistical tests are applied (Lisowski et al., 1974; Atchley et al., 1976). In this analysis, following the work of Kidd *et al* (1996), the use of ratios was to emphase the mechanical aspect of the bone shape (ie. the likely direction of movement) rather than to reduce the effect of size.

All ratio data was found to be normally distributed allowing parametric analysis to be carried out.

Bones from both left and right feet were measured in some subjects. The null hypothesis of no difference between sides was tested using paired t-tests. There was no significant difference in any of the measurements for the 13 pairs of metatarsal bones, 10 pairs of cuneiforms and 6 pairs of naviculae. The 11 pairs of tali showed a significant difference between the left and right talar body-neck angle (ABC:DEF), talar head torsion angle (ABC:GHI) and length measurements.

3.51 The TALUS

Table 8 shows the data for the male and female tali.

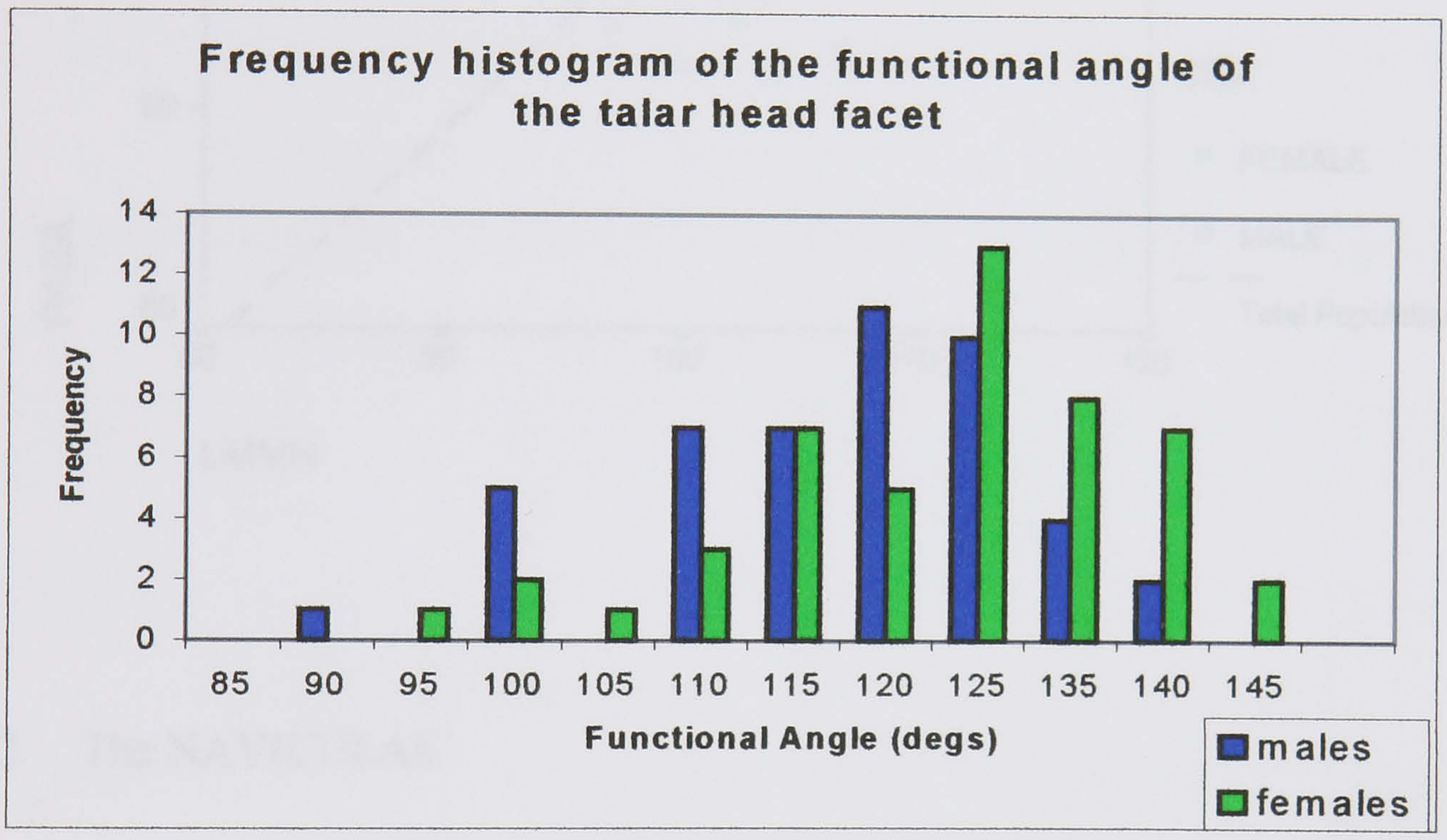
A t-test was used to test for differences in the male and female talar measurements. The talar head torsion angle was found to be significantly different between the sexes ($p = 0.03$) with males having a greater angle than females (mean difference = 3.01°, 95% CI = 2.42°-5.79°). The maximum functional length and width of the bone was significantly different between the sexes as would be expected ($p < 0.001$).

Table 8. Tali results

Group		mean	Std Dev	Mean diff	95% CI	P value
ABC:DEF (degs)	male	18.74	4.42	-0.25	-1.89 – 1.4	p=0.77
	female	18.98	4.18			
ABC:GHI (degs)	male	38.09	7.87	3.01	-2.42 – -5.79	p=0.03
	female	35.08	6.47			
Length (mm)	male	52.59	3.14	5.74	4.61 – 6.87	p<0.001
	female	46.85	2.72			
Width (mm)	male	38.03	2.42	3.77	2.95 – 4.59	p<0.001
	female	34.36	1.78			
Head facet Length (mm)	male	29.52	2.53	3.38	2.5 – 4.27	p<0.001
	female	26.13	2.05			
Head facet width (mm)	male	19.23	2.25	1.96	1.21 – 2.7	p<0.001
	female	17.26	1.54			
Ratio len / width	male	1.55	0.16	0.03	-0.031– 0.044	p=0.36
	female	1.52	0.14			
F angle head (degs)	male	117.45	11.07	-4.91	-9.24 - -0.56	p=0.03
	female	122.35	11.58			
PASA (degs)	male	101.7	4.84	-0.97	-2.8 – 0.86	p=0.3
	female	102.67	4.71			
LM-MN (degs)	male	103.29	4.31	0.24	-1.5 – 1.98	p=0.79
	female	103.05	4.78			

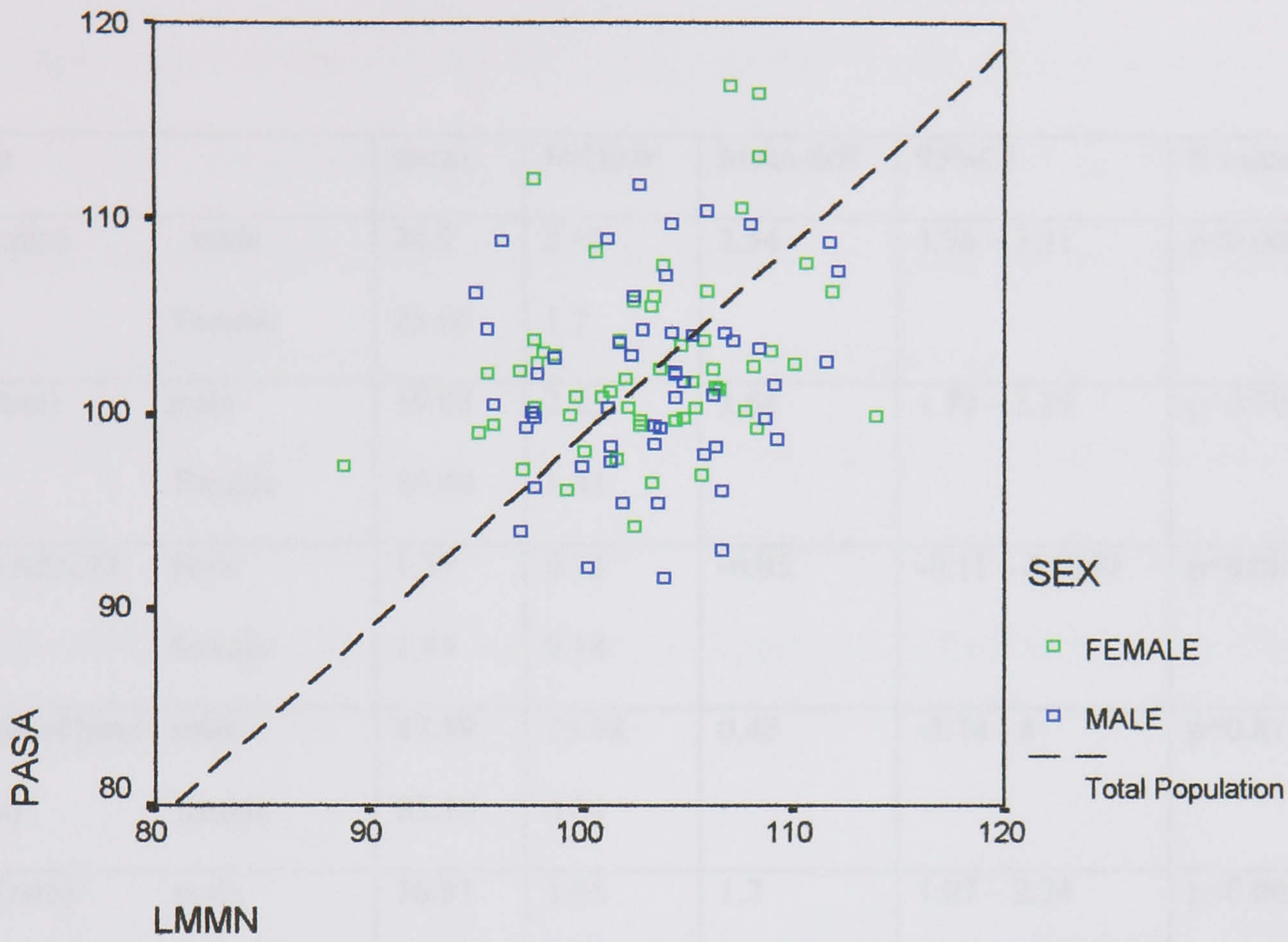
The value of facet length / width was calculated for the head facet in order to describe the shape of the facet with a value of 1 indicating a round surface and a value >1 indicating an oval surface increased in the direction of the length of the facet. No significant difference was found (p = 0.36). The radius of the talar head facet was greater in males (mean difference = 2.36°). When the functional angle was calculated using the chord length (OP), a significant difference between the sexes was found with females demonstrating a greater functional angle (mean difference = 4.91°, 95% CI = 9.25° - 0.56°), indicative of a more curved facet ($p = 0.027$) (see figure 45).

Figure 45. Histogram showing the male and female functional angles of the talar head facet.



The direction of the talar head calculated using the proximal articular set angle showed no significant difference between males and females ($p = 0.3$). The angle created between lines formed from the width of the talus (LM) and the line from the lateral malleolus to the centre of the talar head (MN) also showed no significant difference ($p=0.79$). There appeared to be no correlation between these measurements (see figure 46) despite similar mean values and no significant difference between the measurements as assessed by a paired t-test ($p = 0.09$).

Figure 46. Scatter plot showing the relationship between the PASA and LM-MN with regression line through the mean of the total population.



3.52 The NAVICULAE

Table 9 shows the data for male and female naviculae

Table 9. Naviculae Results

Group		mean	Std Dev	Mean diff	95%CI	P value
AB (mm)	male	26.2	2.18	2.54	1.76 – 3.31	p<0.001
	Female	23.66	1.7			
CD (mm)	male	19.03	2.25	2.54	1.79 – 3.29	p<0.001
	Female	16.49	1.43			
Ratio AB/CD	male	1.39	0.16	-0.05	-0.11 – 0.0069	p=0.08
	female	1.44	0.14			
F angle of head (degs)	male	87.59	10.98	0.43	-3.14 - 4	p=0.81
	female	87.16	6.34			
AF (mm)	male	16.81	1.85	1.7	1.07 – 2.34	p<0.001
	female	15.11	1.38			
BG (mm)	male	11.39	1.85	1.07	0.43 – 1.72	p<0.001
	female	10.32	1.37			
Ratio AF/BG	male	1.5	0.23	0.21	-0.061 – 0.1	p=0.61
	female	1.48	0.19			
FHI:GHI (degs)	male	151.14	6.3	0.26	-1.93 – 2.46	p=0.81
	female	150.87	4.67			
FKJ (degs)	male	31.26	11.86	2.34	-1.89 – 6.56	p=0.27
	female	28.92	9.36			
FJ chord (mm)	male	18.22	1.8	1.22	0.54 – 1.89	p=0.001
	female	17	1.62			
F angle (degs)	male	41.84	6.49	1.65	-1.6 – 4.99	p=0.33
	female	40.18	7.86			

The naviculae showed significant differences between males and females in the length and width of the talar head facet (AB and CD). The value of length / width (AB/CD) was used to describe the shape of the facet. Females showed a larger value (mean = 1.44) than males (mean = 1.39) indicating that the female facet was more oval in shape, having a greater length than width measurement. However the difference was not large enough to reject the null hypothesis of no difference between the sexes ($p = 0.08$) and the differences is probably too small to be of interest.

The medial and lateral width of the navicular was significantly greater in males than females ($p < 0.001$) but when the value of medial width / lateral width was calculated to describe the wedge shape of the bone, no significant difference between the sexes was found ($p = 0.61$).

The radius of the curve of the talar head facet (AEB) was significantly greater in males however when the functional angle was calculated using AB as chord length, showed no significant difference between males and females ($p = 0.801$).

The alignment of the medial cuneiform facet compared to the lateral and intermediate cuneiform facets combined (FHI:GHI) was measured across the centre of the facets. No significant difference in angle was found between the sexes ($p = 0.81$).

The shape of the medial cuneiform facet on the navicular was classified through direct observation. The facet was described as concavoconvex in 6 males and 12 females, flat in 5 males and 4 females and rounded in 38 males and 37 females. A chi-squared test showed that there was no significant difference in facet shape between the sexes ($p = 0.39$). The functional angle of the "round" facets only was calculated since the radius of curvature of the flat or concavoconvex surfaces could not be measured. The functional angle of curvature (radius – FJK, chord - FK), showed no significant difference between males and females ($p = 0.33$).

3.53 The MEDIAL CUNEIFORM

The medial cuneiform showed no differences in the angle of the navicular facet measured by Schultz's method (ABC:DEF) or the new method (ABC:ABI). A good correlation existed between the measurement techniques ($r = 0.76$) although the measurement error was lower with the new method (2.57° vs 3.89°).

The radii of the curvatures of the navicular facet GHI (allowing abduction / adduction) and DIJ (allowing dorsiflexion / plantarflexion) showed no differences between the sexes despite the chord lengths for both joint surfaces (GH and DJ) being significantly larger in males ($p < 0.001$). The functional angle of the navicular facet in the direction GHI was not found to be significantly different between males and females although the 95% confidence interval for the mean is wide with the upper level for the mean difference value being as great as 9 degrees. However, the functional angle DIJ was significantly different ($p = 0.002$) with males showing a greater functional angle in the direction of abduction / adduction of the cuneiform on the navicular (see figure 47). In both directions of movement, the male bones show greater functional angles.

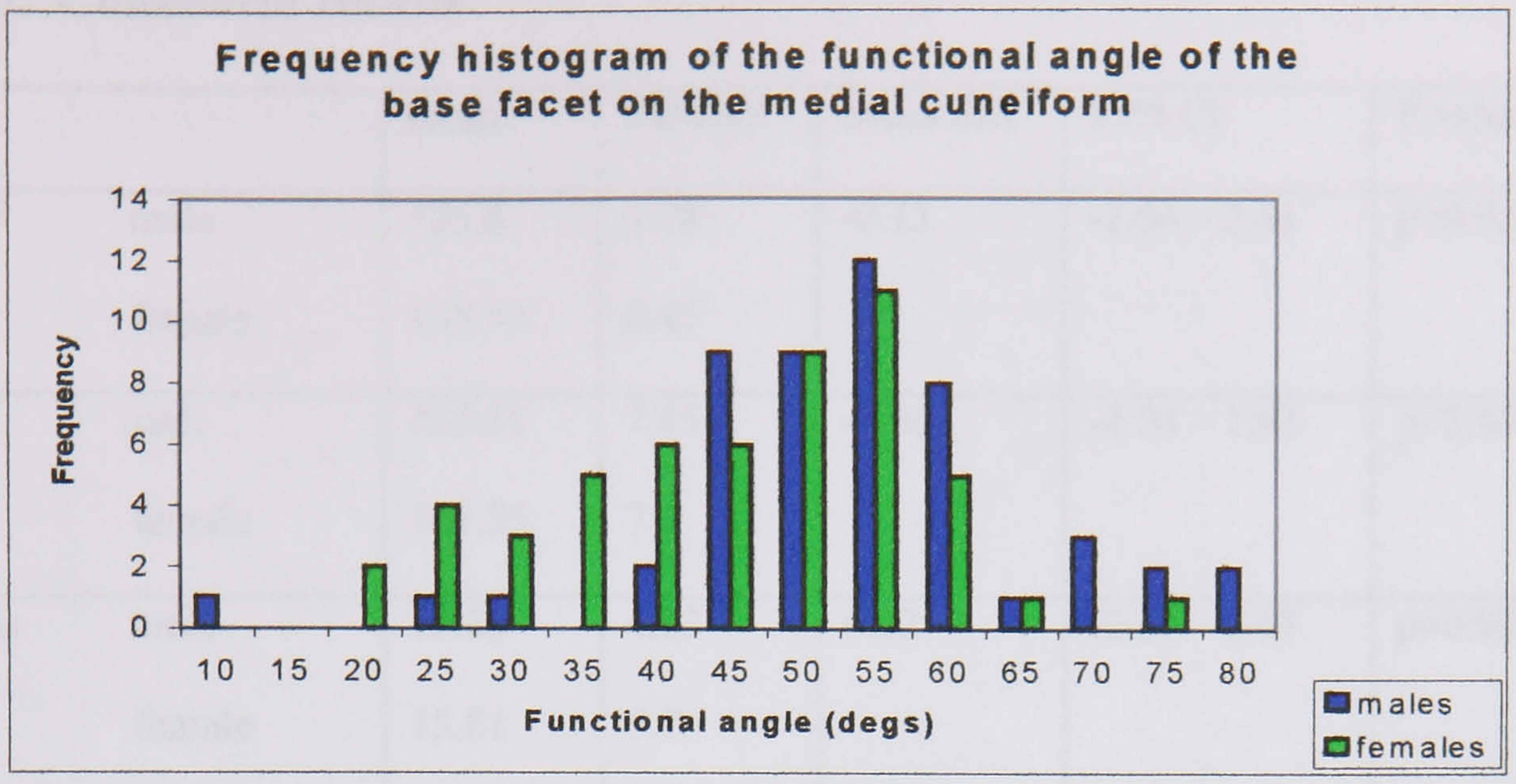


Figure 47. Histogram showing the male and female functional angle of the cuneiform base facet (DIJ) which allows movement in abduction / adduction.

The radius of the curve at the centre of the facet for the 1st metatarsal base showed a significant difference with males having a larger radius of curvature ($p = 0.003$) and also a greater chord length ($p < 0.001$). When the functional angle for curvature of the 1st metatarsal base was measured, the females were shown to have a greater curvature but the result was not significant ($p = 0.15$).

The results for the medial cuneiform are shown in table 10.

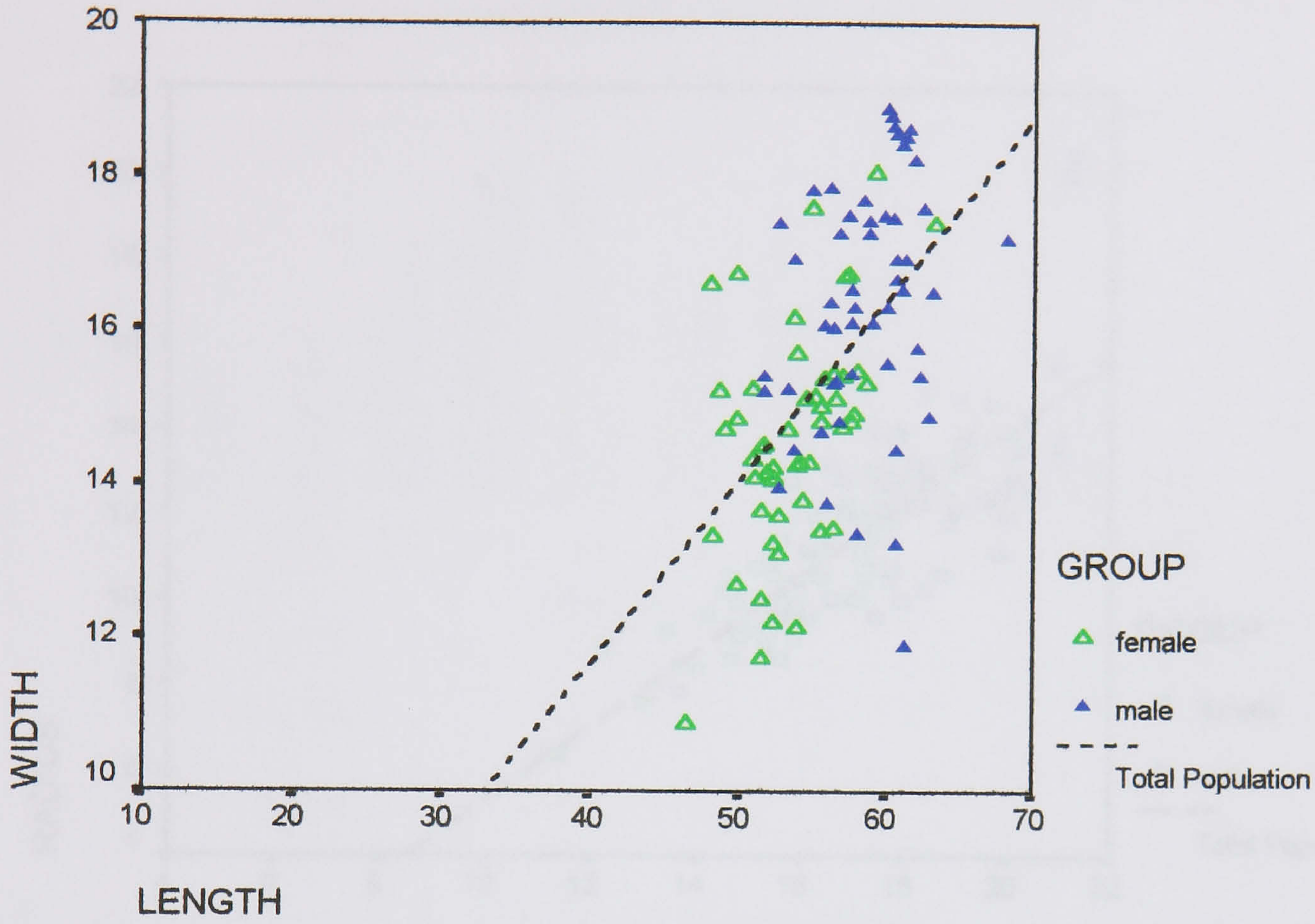
Table 10. Cuneiform results

Group		mean	Std Dev	Mean diff	95% CI	P value
ABC:DEF	male	135.8	6.76	-0.13	-2.64 – 2.41	p=0.92
(degs)	female	135.93	6.47			
ABC:ABI	male	105.41	7.65	-1.06	-4.03 – 1.92	p=0.48
(degs)	female	104.35	7.8			
GHI radius	male	15.83	4.83	0.02	-2.03 – 2.07	p=0.98
(degs)	female	15.81	5.7			
GH chord	male	10.2	1.54	1.36	0.85 – 1.87	p<0.001
(mm)	female	8.84	1.05			
F angle GHI	male	40.33	12.58	4.04	-0.63 – 8.7	p=0.09
(degs)	female	36.29	11.6			
DIJ radius	male	17.65	3.71	0.36	-1.12 – 1.84	p=0.63
(degs)	female	17.29	3.83			
DJ chord	male	14.58	1.94	2.31	1.61 – 3.0	p<0.001
(mm)	female	12.27	1.62			
F angle DIJ	male	50.38	12.65	7.97	3.1 – 12.85	p=0.002
(degs)	female	42.41	12.65			
CLK radius	male	16.6	7.93	4.1	1.42 – 6.78	p=0.003
(degs)	female	12.5	5.49			
CL chord	male	7.83	1.5	1.22	0.71 – 1.73	p<0.001
(mm)	female	6.61	1.13			
F angle CLK	male	31.49	14.14	-3.78	-9.0 – 1.43	p=0.15
(degs)	female	35.27	12.85			

3.54 The 1st METATARSAL

The 1st metatarsal showed size differences in both length and width as expected (see figure 48) with the male metatarsals being significantly larger ($p < 0.001$).

Figure 48. Scatter plot of length vs width for the 1st metatarsal with regression line through mean of the total population.

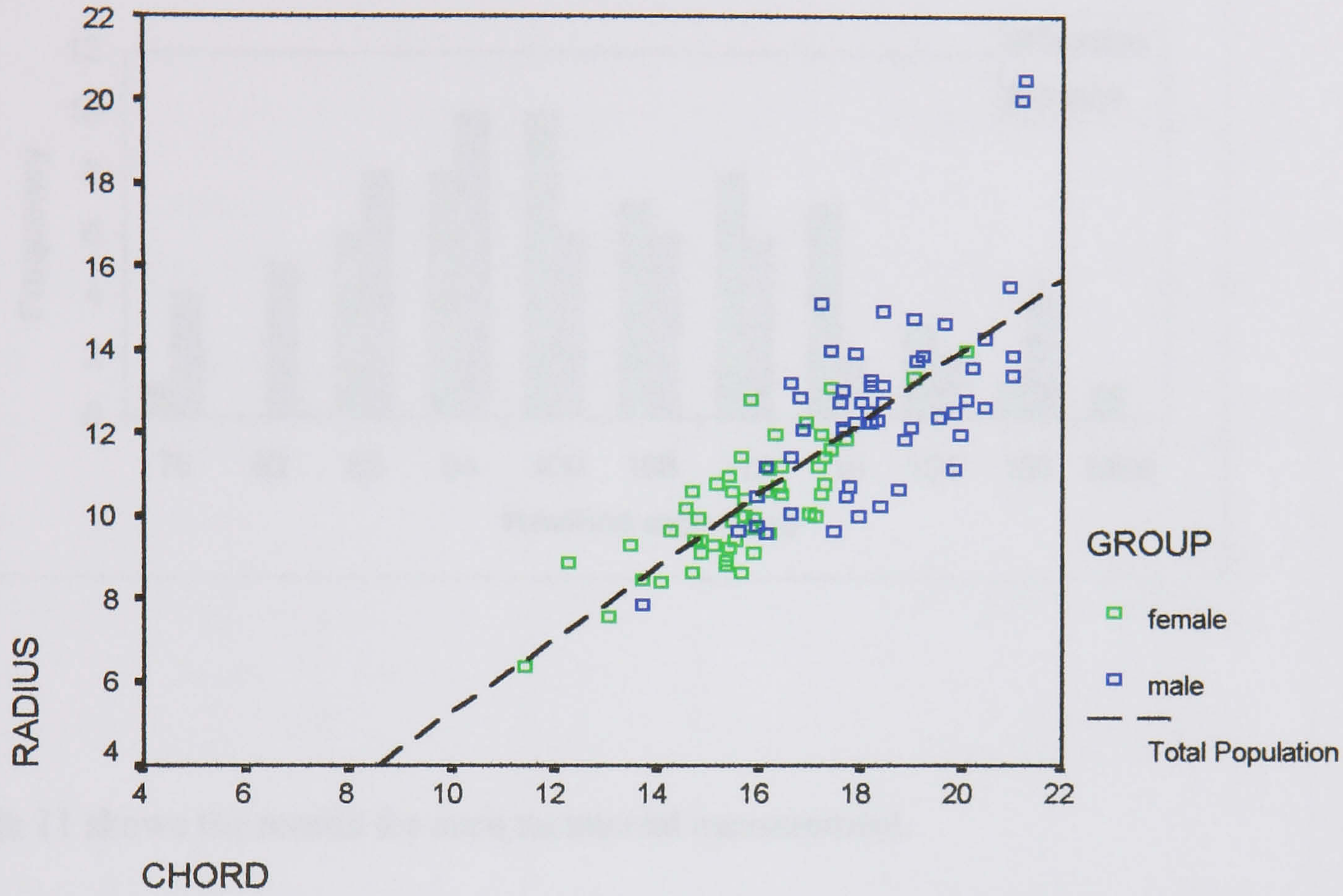


The alignment of the tarsometatarsal joint facet (MC plane) was shown to have an increased angle in females. The mean difference between males and females was small but the 95% CI showed a lower limit for the difference as 3.2 degrees. The difference between males and females was just above the chosen level of probability for the study ($p = 0.055$).

The metatarsal head was shown to have a greater radius of curvature and chord length in males compared with females ($p < 0.001$).

The chord length for the metatarsal head and the radius of the curve of the metatarsal head was significantly greater in males than females (see figure 49).

Figure 49. Scatter plot of male and female metatarsal head chord length and surface radius with regrssion line through the mean of the total population.



However when the functional angle of the head of the metatarsal was calculated, the angle was found to be significantly greater in females (p = 0.047) with the mean difference having an upper level for the 95% CI as great as 11 degrees difference (see figure 50).

Figure 50. Frequency graph of the functional angle of the metatarsal head.

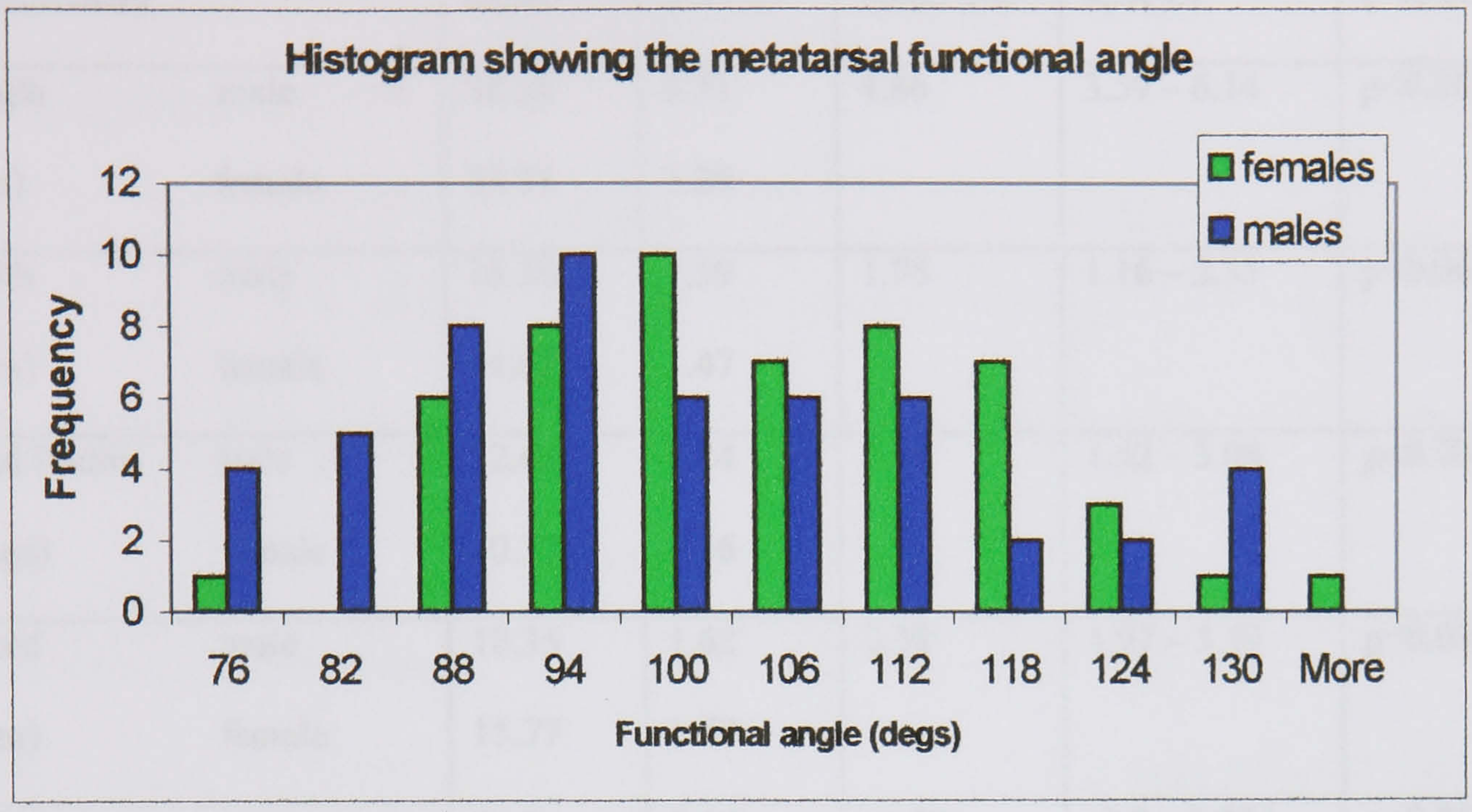


Table 11 shows the results for each metatarsal measurement.

Table 11. Metatarsal results

Measurement		mean	Std Dev	Mean diff	95% CI	P value
Length	male	58.58	3.31	4.86	3.59 – 6.14	p<0.001
(mm)	female	53.71	3.29			
Width	male	16.38	1.59	1.75	1.16 – 2.35	p<0.001
(mm)	female	14.63	1.47			
Head Radius	male	12.62	2.24	2.35	1.62 – 3.08	p<0.001
(degs)	female	10.27	1.46			
Chord	male	18.35	1.62	2.58	1.97 – 3.19	p<0.001
(mm)	female	15.77	1.53			
MC plane	male	96.7	3.94	-1.59	-3.2 – 0.034	p=0.055
(degs)	female	97.34	5.87			
PASA	male	91.82	5.95	-1.08	-3.21 – 1.05	p=0.97
(degs)	female	92.9	5.01			
Functional angle	male	96.72	15.97	-5.56	-11.0 - -0.075	p=0.047
(degs)	females	102.29	12.13			

3.55 Overall potential differences in abduction / adduction position of the 1st metatarsal between males and females.

When the means of the significant angles for all the bones are added together, it can be seen that females have a potential 12.06 degrees difference in position compared with 7.97 degrees in males. If the maximum difference is calculated from the upper limit of the 95% confidence interval of the mean, the difference increases to 23.34 degrees in females compared with 12.85 degrees in males. Table 12 shows where the differences occur.

Table 12. Differences in the potential adduction of the first metatarsal between males and females.

	Female	Male
Initial	0°	0°
Talar head functional angle F>M	4.91° (upper 95% CI = 9.24°)	
Medial cuneiform DIJ angle M>F		7.97° (upper 95% CI = 12.84°)
1st Metatarsal base angle F>M	1.59° (upper 95% CI = 3.2°)	
1st Metatarsal head functional angle	5.56° (upper 95% CI = 11°)	
Final total	**12.06°** **(upper 95% CI =23.34°)**	**7.97°** **(upper 95% CI = 12.84°)**

Logistic Regression was applied to each bone in order to investigate the usefulness of each measurement in determining the sex of each bone. The measurements were entered in a stepwise method to identify those that were important in the analysis. Table 13 shows the percentage accuracy of prediction for each of the bones measured for the final steps in the calculation. Appendix IV shows the predicted probabilities plots for each of the bones.

Table 13. Classification Table

	Observed		Predicted SEX		Percentage Correct
			MALE	FEMALE	
TALUS	SEX	MALE	45	7	86.5
		FEMALE	8	47	85.5
	Overall %				**86.0%**
			MALE	FEMALE	
NAVICULAR	SEX	MALE	39	10	79.6
		FEMALE	8	45	84.9
	Overall %				**82.4%**
			MALE	FEMALE	
Medial CUNEIFORM	SEX	MALE	36	13	73.3
		FEMALE	12	39	76.5
	Overall %				**75%**
			MALE	FEMALE	
1st METATARSAL	SEX	MALE	45	8	84.9
		FEMALE	7	43	82.7
	Overall %				**83.8%**

The talus had 86% prediction accuracy with the length and width being the only two significant contributors (see table 14)

Table 14. Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1	LENGTH	-.654	.119	30.434	1	.000	.520
	Constant	32.534	5.909	30.319	1	.000	1.3E+14
Step 2	LENGTH	-.451	.138	10.687	1	.001	.637
	WIDTH	-.460	.200	5.293	1	.021	.631
	Constant	38.985	7.357	28.082	1	.000	8.53E+16

a Variable(s) entered on step 1: LENGTH.

b Variable(s) entered on step 2: WIDTH.

For the navicular, an 82.4% accuracy in prediction was found with the important measurements being the long (AB) and short (CD) talar facet dimension and the medial width of the bone (AF).

The medial cuneiform showed a prediction accuracy of 75% with 3 measurements being important in the prediction – the chord length of the navicular facets (DJ and GH) and the radius of curvature of the distal facet for the metatarsal (CLK).
The 1st metatarsal showed an 83.8% prediction accuracy with the bone length, PASA and radius of the curvature of the metatarsal head being important factors.

In all cases of logistic analysis, the Hosmer and Lemeshaw Chi square statistic showed a good fit for each model ($p \geq 0.21$).

3.6 Discussion

This study used a novel measurement technique. Despite some differences in the method used, limited comparison was possible with other published results, on similar subjects, suggested that the new technique provided similar results given that the specimens are from different populations (see table 15).

Table 15. Comparison of measurement technique with other studies

	Rhoads and Trinkaus (1977)	Kidd et al (1996)	Steele (1976)	Ferrari and Linney
Mean talar length	53.59 - 48.08mm		55.3mm males 49.7mm females	52.59mm males 46.85mm females
Mean talar width			43mm males 38.6mm females	38.03mm males 34.36mm females
Talar neck angle	25.76-24.06°	18.56° male 18.94° female		18.74° male 18.98° female
Talar neck torsion angle	42.78-40.32°	45.17° male 45.16° female		(90-38.09) = 51.91° male (90-35.08) = 54.92° female

This is the first study to use a hand held laser scanner for the measurement of foot bones. Although 3D scanning has been available for the measurement of bones previously, it has had limited application since the machines have been too large to take to the collections and it is inappropriate to move large numbers of bones to the scanners. The hand held scanner has the advantage of being portable and once the bones have been scanned, a permanent visual record of the bone is created that can be used on subsequent occasions for further measurement without the need to return to the collections. The software used to measure the bones allowed marker placement to be made both visually, as would occur with other techniques, but also aided with the use of contour lines which identify very small deviations in the bony surface.

The results showed no differences between left and right sides for most measurements as would be expected. The exception to this was the talar body-neck angle. The measurement of the angle between planes is highly sensitive and a small tilt in one of the two planes can greatly change the angle recorded. The mean value of 5 repeated measurements reduced some of the possible error but it may have been necessary to increase the number of repeats for certain measurements in order to show no difference between sides, particularly when dealing with such a small sample size (n = 11). The repeatability tests of the linear measurements for example, showed a difference of less than 2mm between the 5 repeats but the measurements between two planes, although repeatable, showed a larger measurement error (Appendix III). The mean difference between left and right talar neck angles was only 2 degrees (95% CI = 0.74 – 3.4 degs) so the difference is probably not sufficiently great to be important in terms of changing function.

Several differences between male and female foot bones were found and these were principally due to size. As expected, in measurements involving length and width, male bones were always larger than female bones. This was also true of joint sizes where chord lengths and radii were greater in males. This information alone does not identify whether functional differences exist and so functional angles and angular measurements taken. The functional angle of a joint surface provides an angular measurement of the potential movement that can occur at a joint surface before subluxation occurs; comparison between bones is made with the assumption that all other factors that control joint movement (for example, cartilage thickness, ligament placement and capsule strength) are equal. Differences in the functional angle between males and females were sought in order to investigate whether any of the movements could account for increased adduction of the 1st metatarsal in the female foot and thus be associated with HAV deformity. Three significant differences in functional angles were found and these are summarised in table 16.

Table 16. Summary of significant findings for functional angle measurements

Measurement	mean	Std Dev	Mean diff	95% CI	P value
Metatarsal head Functional angle (degs) male	96.6	15.92	-5.7	-11 - -0.075	p=0.04
female	102.3	12.15			
Medial cuneiform Functional angle DIJ (degs) male	50.38	12.65	7.97	3.1 – 12.85	p=0.002
female	42.41	12.65			
Talus Functional angle (degs) male	117.45	11.07	-4.91	-9.24 - -0.56	p=0.03
female	122.35	11.58			

The functional angle of the metatarsal head was greater in females than males. Although this was not related to the adduction of the metatarsal, it was sought as a possible association with the bunion deformity since a greater curvature of the metatarsal head may be related to the ability of the proximal phalanx of the hallux to move around the metatarsal, creating a greater degree of deformity. An increased functional angle of curvature of the metatarsal head had previously been found in the radiographic studies (chapter 2) and this 3D study was able to confirm the findings of the 2D studies in a different population. The PASA of the metatarsal head was not found to be significantly different between the sexes. This finding also concurs with the results of the radiographic study.

The functional angles of the joint facet on the medial cuneiform for the navicular showed male and female differences. The functional angle of the facet for the navicular was significantly greater in males than females in the direction of abduction / adduction (points DIJ in figure 39, pg 104) and was greater in dorsiflexion / plantarflexion although the difference did not reach the chosen level of significance. This was unexpected as it would be associated with an ability to adduct the medial cuneiform, and therefore the metatarsal, in males more than females. However, the angles involved are small suggesting that the joint surface is almost flat. The mean functional angle of DIJ in males was 50.38° whereas in comparison, the functional angle at the metatarsal head was almost twice this at 96.6°. The movement involved at DIJ is therefore very small. The difference between males and females was quite large however, at 7.97°. The movement across the facet in the direction of DIJ was taken to represent abduction / adduction but at this joint it is particularly difficult to confine the description to movement in one plane. The anatomical position of the cuneiform is dependant on the alignment of the navicular. In an articulated skeleton, the medial cuneiform is slightly tilted so that movement through the curve DIJ is actually in a direction of abduction with dorsiflexion and adduction with plantarflexion. If the navicular was more everted, the position of DIJ would change so that the movement becomes dorsiflexion / plantarflexion. Having said this, the measurement of the functional curve at the facet representing dorsiflexion / plantarflexion (points GHI in figure 39) was also increased in males, but did not reach the chosen level of statistical significance ($p = 0.09$). With a change in alignment of the navicular, the curvature along GHI would provide abduction / adduction and so in either case, it would appear that the movement is greater in males.

At the talar head, the functional angle was significantly greater in females indicating that the motion at that joint would be increased in females compared to males if all other factors influencing movement at a joint where equal between the sexes. The movement would be increased in the direction of adduction with plantarflexion and abduction with dorsiflexion.

Of the three significant functional angles found, two showed greater movement in females compared to males and both of these could influence movement in the direction of adduction of the metatarsal or abduction of the hallux. Latimer and Lovejoy (1989), who first introduced the use of the functional angle noted that female gorillas had a greater functional angle at their joints than male gorillas.

Several significant differences in angular measurements were found. The angle of the facet on the metatarsal base for the medial cuneiform was at the chosen level of significance for this study. Females had a greater angle of the metatarsocuneiform facet than males and so when articulated, this would result in greater adduction of the metatarsal on the cuneiform in women compared to men (see figure 51).

The reciprocal facet on the anterior surface of the medial cuneiform did not show a difference between the sexes.

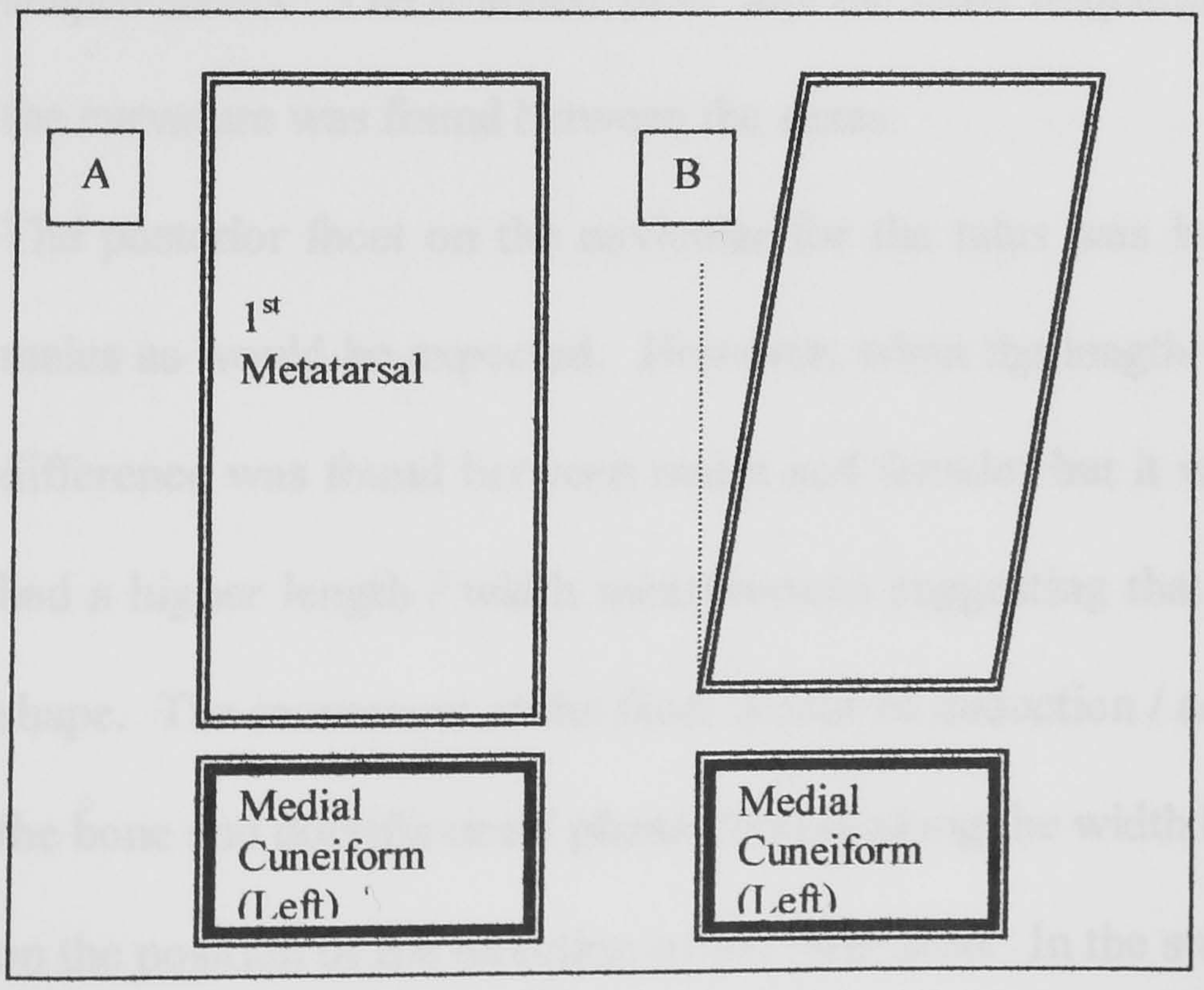


Figure 51. diagramatic representation of the alignment of the left 1st metatarsal on the medial cuniform when the metatarsal base has a 90 deg angle (A) and when an acute angle is present resulting in adduction of the metatarsal (B).

The talar neck torsion angle was found to be significantly different between males and females with males having a greater angle, which would indicate that the talar head was less everted and so more horizontal, in males than in females. The difference was small (mean difference = 3.02°) but suggests that the navicular will be more horizontally placed in the male, allowing more abduction / adduction at this joint whilst females would have more dorsiflexion and plantarflexion available at the joint. The fact that the navicular is potentially more horizontal in males has an impact on the position of the medial cuneiform. The curve of the base facet of the medial cuneiform in the direction of ad/abduction (DIJ) will change to represent dorsiflexion / plantarflexion. Thus the significant difference found between male and females for DIJ may not represent a difference in the degree of adduction available.

The facet for the medial cuneiform on the navicular is known to be quite variable and this study confirmed this identifying the existence of flat, round and concavoconvex shaped facets. The rounded facet was the most frequently seen and no difference in the curvature was found between the sexes.

The posterior facet on the navicular for the talus was larger in length and width in males as would be expected. However, when the length was divided by the width, a difference was found between males and females but it was not significant. Females had a higher length / width measurement suggesting that the facet was more oval in shape. The movement at the facet would be abduction / adduction along the length of the bone and dorsiflexion / plantarflexion along the width but this would be dependant on the position of the direction of the talar head. In the study, the measurements were taken with the navicular positioned with the plantar surface in the horizontal plane. When articulated, the navicular is tilted to the horizontal due to the torsion in the talar neck. The movement along the length of the facet would not be pure abduction / adduction but a component of movement in several planes.

It is recognised that reference to the position of each bone to its neighbour in this study is based upon simple re-articulation of the bones visually and that when the foot functions, the bones may change alignment considerably. Thus movements thought to be abduction / adduction may change to dorsiflexion / plantarflexion (or visa versa) when the foot is weightbearing. The function of an individual's feet is dependent on many factors such as their biomechanical alignment and overall joint flexibility. Throughout the study, an attempt has been made to use standardised reference positions so that comparisons can be made with other studies in this field.

It was also noted that reciprocal joint surfaces often did not have matching curvatures. For example, the talar head functional angle of curvature was approximately 117 degrees, whereas the curvature of the reciprocal facet on the navicular was 87 degrees. To improve joint congruence, the depth of the joint will be enhanced by the shape and thickness of the articular cartilage as well as by surrounding ligaments and joint capsule. Such structures may influence both the degree and direction of the movement at the joint.

In respect to the evolution of the feet and the forward facing alignment of the 1st metatarsal, there was no evidence that major changes had taken place in the male foot bones but not the female bones. Despite some variation in the roundness of the articular facets which may affect the 1st metatarsal position during function, the angles that have interested anthropologists in the investigation of arborialism and bipedalism (the base of the 1st metatarsal, the anterior facet on the medial cuneiform and the degree of wedging of the navicular) all showed no significant difference between males and females. Differences identified between males and females are more probably related to extrinsic factors such as occupation and footwear influencing bone shape than different rates of evolution.

Considering the individual bones, male and female differences did exist and allowed the gender of a bone to be predicted with an accuracy of up to 86%, which compares well with the forensic studies quoted. This study has found similar identification rates to other studies such as Steele (1976), who had a prediction accuracy of 81% for the talus (compared to 86% in this study) and Smith (1997), who had an 84% prediction accuracy for the metatarsal (compared to 83.8% in this study). Interestingly the measurements most important in discriminating between the sexes proved to be the linear dimensions rather than the significant functional and angular measurements identified. The 3D method applied in this study may therefore be useful for forensic purposes, to aid identification of an individual where other bones, such as the pelvis, are missing.

Although this study has generally linked the functional and angular findings to the potential to create an adducted 1st metatarsal position and thus cause HAV deformity, it must also be considered that the angles seen may be as a result of HAV deformity. As discussed in chapter 2, if HAV deformity is present in females more than males, the sexual dimorphism seen in the different bones may be due to the presence of the deformity or have been brought about by environmental differences between males and females. The medical literature describes the treatment of HAV deformity as early as the 13th century with surgical treatments being started in the late 19th century (Dagnall, 1994). Therefore the condition may have been present in the population of Huguenots but no prevalence data exists to inform us on the exact numbers affected.

Males and females would have had similar environmental conditions – undertaking common occupations – so the function of the feet would have been similar and functional differences would not be expected. As the skeletons were disarticulated, it is also impossible to tell the prevalence of HAV deformity in this population. So whilst accepting that the differences found in this study in male and female feet may be as a result of HAV deformity being more prevalent in the women, it is also possible that the differences are naturally occurring and thus be considered to be predisposing factors to HAV deformity in women.

3.7 Conclusion

A new method for bone measurement has been introduced that uses the original planar measurements suggested by Lisowski that have not been possible with earlier techniques. The method has produced comparable results to other studies for measurements of the talus and has found that the sex of a subject may be predicted to an accuracy of up to 86% using simple linear measurements and measurements of facet curvature.

Several measurements were found to be significantly different between males and females which may lead to, or be the result of, functional differences occurring between male and female feet, but at rest the alignment of the bones would be expected to be similar. Overall, there was a tendency for the measurements to show that increased adduction of the metatarsal and abduction of the hallux may occur in the female foot thus suggesting that the female foot has an underlying anatomical predisposition to 1st metatarsal adduction and thus hallux abductovalgus formation.

3.8 Publications

The following article has been accepted for publication:

Ferrari J, Hopkinson D, LinneyA. An investigation of the size and shape differences between male and female bones: Is the female foot predisposed to HAV deformity? Journal American Podiatric Medical Association 2004.

CHAPTER FOUR JOINT HYPERMOBILITY AND HAV DEFOMITY

Introduction

Aims

Data Analysis

Methods

Results

Discussion

Conclusion

Publications

CHAPTER FOUR

JOINT HYPERMOBILITY:
- **THE USE OF A NEW ASSESSMENT TOOL IN CHILDREN**
- **ASSESSMENT OF THE RELATIONSHIP BETWEEN HALLUX ABDUCTOVALGUS AND HYPERMOBILITY IN CHILDREN.**

4.1 Introduction

People who exhibit an excessive range of motion at a number of their joints – hypermobility – have been recognised for many centuries. Hipprocrates is named as the first person to describe people with gross joint mobility in the 4th century BC (Al-Rawi and Nessan, 1995) but the majority of descriptions of hypermobility in more modern texts have been made with reference to the hypermobility occurring as part of a systemic disorder. The two best known conditions which feature hypermobility are Marfan's syndrome and Ehlers-Danlos syndrome, but there are many other conditions such as Type I Osteogenesis Imperfecta, Pseudoxanthoma elasticum and homocystinaemia: these are often familial in origin (Beighton et al., 1988). That joint hypermobility could cause musculoskeletal disorders in the absence of systemic disease was recognised in 1967 (Kirk et al., 1967). Following this, various names were used for the condition such as "hypermobility syndrome", "hypermobile joint syndrome", "familial joint hypermobility syndrome" before the term "benign joint hypermobility syndrome (BJHS)" came into regular use. There is still much debate as to whether BJHS is part of the spectrum of disorders seen with Ehlers-Danlos syndrome (EDS). For example, type III EDS has primarily joint problems but the skin involvement (hyperextensibility, scarring and bruising) is extremely variable (Clarke et al., 2002). Subjects with BJHS may appear very similar to this but do not appear to have the defects in synthesis in type I or type III collagen as is seen in EDS (Gedalia et al., 1985.)

The degree of hypermobility found in a person is known to vary with age, sex and ethnic group. Hypermobility is more common in women than men at every age (Beighton et al., 1973; Hudson et al., 1998; Jesse et al., 1980). Young people are known to have more flexible joints than adults with flexibility reducing greatly after the age of 20 years (Beighton et al., 1973; Hudson et al., 1998). Asian and African populations are reported to be more hypermobile than Caucasians (Beighton et al., 1973; Hudson et al., 1998). Prevalence rates vary for many populations due to ethnic differences as well as arbitrary selection of the defining "cut-off" point in the assessment scale used. For example in school children the prevalence of joint hypermobility has been reported as 32% of Brazilian children (Forleo et al., 1993), 16% of Egyptian children (El-Garf et al., 1998) and 12% of British children (Gedalia et al., 1985). A study of American blood donors found a prevalence of 5% in adults, none of whom showed any signs of the collagen disorders seen in EDS type III (Jesse et al., 1980).

The musculoskeletal symptoms related to hypermobility are various and include recurrent injuries such as sprains and dislocations, tendinitis, bursitis, bruising, varicose veins, nerve compression, delayed motor development and early osteoarthritic change (Russek, 1999; Hudson et al., 1998). Such conditions are likely to result in presentation to a rheumatology clinic with suspected rheumatic disease although the diagnosis of hypermobility is often delayed due to the paucity of knowledge about the condition (Grahame, 2001). Hypermobility has been reported as being responsible for 25% of referrals to rheumatologists (Hudson et al., 1998). Other practitioners may also see patients with hypermobility since the condition is also associated with mitral valve prolapse (Russek, 1999), genitourinary conditions (Bai et al., 2002) and panic attacks / anxiety states (Bulbena et al., 1992).

Hypermobile children suffer from similar joint complaints to adults and in one prospective study, up to 40% of hypermobile children developed symptoms of arthralgia in the course of one year (Gedalia and Press, 1991). Delayed motor development in children has also been described (Russek, 1999). The lower limb is the region most often affected (Gedalia et al., 1985; Biro et al., 1983) with knee pain, related to conditions such as chondromalacia patellae, being common (Al-Rawi and Nessan, 1997). The foot pathology has also been reported with reference to joint hypermobility (Finsterbush and Pogrund, 1982). The foot may be affected in isolation with conditions such as excessive pronation (flat feet), tarsal tunnel syndrome and hallux valgus being reported (Francis et al., 1987; Childs, 1986; Harris and Beeson, 1998b). The foot may also be subjected to abnormal forces created by instability in other joints or may be responsible for creating abnormal forces in proximal joints. For example, pes planus was significantly more common in patients with chondromalacia patellae (Al-Rawi and Nessan, 1997). A pronated foot position would cause internal rotation of the tibia and flexion of the knee. This would lead to a mechanically unsound knee with resultant muscle wasting of the vastus medialis muscle and result in abnormal patella tracking and lead to anterior knee pain with a diagnosis of chondromalacia patella.

It has been stated that hypermobility may be an asset. This is thought to be true in situations where the joints are non-weightbearing and need to undergo repetitive movements (Larsson et al., 1993) or where the joints are controlled by strong musculature such as in ballet (Grahame and Jenkins, 1972). However the prognosis of a hypermobile subject is often considered to be poor due to the link between hypermobility and the development of premature osteoarthritis (OA). This link is generally based on clinical opinion although one comparative study has found an association between hypermobility and OA (Bird et al., 1978). The mechanism for this is not clearly understood. It may be that the paucity of collagen in the ligaments that allows the person to be hyper-extendable is also found in the cartilage making it less able to take pressure. It is known that in hypermobility there is a decrease in proprioception that may lead to unsound joint positions being adopted (Hall et al., 1995). It is known that in OA, patients have poor knee proprioception and it has been suggested that this causes the knee to adopt poor mechanical positions and that this is a reason for the OA to occur (Sharma and Yi-Chung, 1997). It is not hard therefore to believe that the lack of proprioception in BJHS may lead to OA in later life. The relationship between OA and hypermobility has not yet been subject to a prospective, long-term study. The association with OA does cause practitioners to take the diagnosis of hypermobility seriously with the maintenance of good skeletal alignment being a primary concern.

Diagnosis of hypermobility is most often made using the criteria developed by Beighton *et al* (1973), which were based on the original assessment of Carter and Wilkinson (Russek, 1999). Carter and Wilkinson used a score that gave a point for any of the following movements:

1. passive apposition of the thumb to the forearm
2. hyperextension of the fingers and wrist so the fingers lie parallel to the forearm
3. hyperextension of the elbow past 10 degrees
4. hyperextension of the knee past 10 degrees
5. excessive dorsiflexion with eversion of the foot.

They proposed that a score of 3/5 indicated hypermobility.

The Beighton score was initially developed for a widespread epidemiological study but has since become the gold-standard for hypermobility testing in the clinical setting. The score includes the thumb, elbow and knee movements as described by Carter and Wilkinson. The fifth finger extension to 90 degrees replaced the finger and wrist movements. The ankle movement is excluded in favour of spinal mobility which is tested by requesting the subject to attempt to place their palms on the ground, keeping their legs straight. The limbs are scored for each side giving a final score to a maximum of nine points. The score allowed the authors to demonstrate how joint flexibility decreases with age and varies with sex (Beighton et al., 1973). At a later date, an arbitrary cut-off point was chosen to indicate hypermobility. The scores of 4/9 for males and 5/9 for females are frequently used to define hypermobility but this arbitrary cut-off point makes the system insensitive and is inappropriate for different ages and different ethnic groups (Van-der-Giessen et al., 2001). For example, one study in Iraq found that 25% of males and 33% of females were "hypermobile" using this threshold (Al-Rawi et al., 1985) when a figure of 5-15% is generally considered "normal" in any population (Hudson et al., 1998). It has been suggested that if hypermobility occurs as part of the extreme range of a normal population then the criteria should identify the percentage of the population that are two standard deviations from the mean of the population studied (ie. 5%) (Fairbank et al., 1984).

The Beighton scale is used to identify generalised hypermobility but is heavily weighted to measurement of the upper limb despite the majority of musculoskeletal complaints presenting in the lower limb. With the Beighton scale, only knee hyperextension is measured in the lower limb. Children or adults presenting with lower limb complaints may fail to be diagnosed if the hypermobility is confined to the lower limb. Bulbena (1992) recognised that certain joint movements are rarely assessed in hypermobility scores giving the example of tibial rotation. There are no good reasons to exclude one joint movement in favour of another. Bulbena also stated that "*the definition of hypermobility should reflect the number of joints involved and the extent to which they move*". Bulbena attempted to address these problems by developing a scoring system based on the scores of Carter and Wilkinson, Beighton and Rotés, as well as adding in a few personal criteria. After initially including many joint motions such as ankle joint dorsiflexion with foot eversion, external shoulder rotation, cervical movement, hip abduction, 1st metatarsophalangeal joint movement and lateral lumber spine flexion, cluster analysis was undertaken to identify the factors that most often identified hypermobility. Ten factors were identified and included in the final scoring system. The resulting system was therefore more extensive than Beighton's with a better balance of upper and lower limb movement. Despite being well tested for external validity and reliability, the score has been little used in hypermobility studies.

Only one scoring system has considered the "feel" of the movement. For example, some joints have an excessive range of motion but firm pressure must be applied to achieve the full movement. In other people, the range of motion is increased but the movement is lax with hardly any pressure being required to move the joint through it's range. Contompasis considered the extent of joint movement by developing a system that graded the degree of laxity for each joint measured. This has been used in a few podiatric studies but was perhaps too detailed for large-scale studies (McNerney and Johnston, 1979).

The foot has received very little attention in relation to generalised hypermobility despite localised hypermobility being recognised since the 1940's when Morton

(1935) described the hypermobile 1st metatarsal. Morton first listed hypermobility as a cause of hallux valgus by describing a metatarsal that underwent a greater range of dorsiflexion when weightbearing. The hypermobility in this case, applied to the first ray movement only was in isolation to any generalised hypermobility problem. One of the first descriptions of hallux valgus occurring in patients with hypermobile joints was in 1952, when the deformity was seen in patients with hypermobile joints that was unconnected to any systemic condition (Mygind, 1953). The author commented on the predominance and predisposition for HAV in females, which is also true for hypermobility (Beighton et al., 1973; Al-Rawi et al., 1985; Larsson et al., 1993; Gedalia et al., 1985). Despite this, to date, it has never yet been suggested that hypermobility may account for the increased female prevalence in HAV deformity.

McNerney and Johnson (1979) undertook the first study of hallux valgus and generalised hypermobility using a group of 50 patients attending a podiatry clinic. Patients with systemic diseases related to hypermobility were excluded. Joint hypermobility was assessed using the criteria devised by Contompasis which included the 5 measures suggested by Beighton *et al* plus a measure of calcaneal stance position. Each measurement was graded according to the severity of the hypermobility. It was found that 70% of patients with marked hallux valgus had high hypermobility scores and the authors felt that excessive motion of the 1st metatarsal due to lax plantar metatarsal ligaments, was the cause of the deformity.

Carl *et al* (1988) followed this study by measuring joint hypermobility in 20 females with HAV deformity and 20 female controls. Using the criteria suggested by Beighton *et al*, the HAV group was found to have a mean hypermobility score of 4.75 (out of 9) compared with 2.35 for the controls. This was a significant difference ($p < 0.01$). The joint movements that were significantly associated with the HAV deformity were found in the hand, suggesting that peripheral hypermobility may be more important than generalised hypermobility. Again, the movement available at the metatarsal-tarsal joint was proposed as the root cause of the deformity. The authors suggested that measurement of the ankle, subtalar and metatarsal joints be measured as they might be of value.

Harris and Beeson (1988a) considered whether the link between HAV and hypermobility was also present in juveniles. A group of 52 subjects, including patients and healthy subjects aged 10-21 years, was separated into those with HAV and those with no deformity after excluding for systemic diseases. The Beighton criteria were applied to measure the degree of hypermobility. The cut-off point to diagnose hypermobility was set at 4/9. There was found to be a significant difference in the hypermobility scores between the two groups with hypermobility being more prevalent in the HAV group but the mean scores for each group are not stated. The study also found a strong association between the HAV angle and age, which might be expected in a younger group when the deformity is developing. As the authors' note, hypermobility reduces with age. This creates some confusion as to the nature of the relationship of hypermobility with HAV deformity since HAV deformity increases with age.

Several studies have attempted to isolate the cause of 1st ray hypermobility (Klaue and Hansen, 1994; Fritz and Prieskorn, 1995; Mizel, 1993). Attention has centred on the metatarsocuneiform joint. When considering hypermobility at the elbow, knees and thumbs, it was found that subjects with thumb hypermobility also had significantly greater metatarsocuneiform movement again suggesting that peripheral hypermobility may be as an important factor in the development of HAV deformity as generalised hypermobility (Fritz and Prieskorn, 1995). There was no correlation with the sex of the subject, which was surprising given the predominance in females for both hypermobility and HAV deformity. Other studies have related the deformity to ineffective soft tissue structures such as the plantar aponeurosis (Rush et al., 2000) and the plantar first metatarsocuneiform ligament (Mizel, 1993). Hypermobility is likely to cause such structures to function ineffectively allowing ground reaction forces to dorsiflex the 1st metatarsal abnormally and thus begin the osseous and soft tissue changes associated with HAV deformity (Root et al., 1977c).

4.2 Aim

This study aimed to test the usefulness of a new lower limb assessment score before assessing the relationship between HAV and hypermobility in a young age group. The scale measured only the joints of the lower limb but included movements of the joints in several planes of motion rather than in just one direction. It included measurements used in other scales but had detailed criteria that had to be met before a joint could be classified as hypermobile.

The study aimed to investigate whether the Beighton score was a reasonable measure of hypermobility in children and to compare the new assessment score as a measure of hypermobility. The study aimed to investigate whether the Beighton score could identify children with lower limb hypermobility. The study investigated the validity of the new scoring system by assessing the correlation with the clinical opinion of the child's flexibility and with the Beighton score. The study compared the LLAS with the Beighton score and considered how many children with lower limb hypermobility were not recognised by the Beighton score or whether the lower limb scale failed to identify children with more generalised hypermobility as defined by the Beighton score.

It was recognised that the use of a cut-off point to classify a patient as "hypermobile" or "normal" is not ideal. The human skeletal system is neither "hypermobile" or "normal" but is a continuum of degrees of flexibility whereby one person may be more flexible than the next but the level at which hypermobility begins is not defined by a single point. The new scoring system was designed to reflect the continuum of flexibility and could therefore be applied to many different populations. However, in order to demonstrate the validity of the system, sensitivity analysis was undertaken to establish a threshold for defining hypermobility.

The individual joint measurements were compared with the overall diagnosis to observe whether measurements of some joints were more useful than others. The interobserver repeatability of the lower limb assessment score was also considered.

The study aimed to consider the relationship between lower limb hypermobility and HAV deformity. The study involved a younger age group than has been used in previous studies in order to determine whether the relationship found in other studies was true in a younger age group, thus allowing early identification of those at risk of HAV deformity. Unlike the previous studies, this study considered lower limb joint hypermobility in a normal population in order to test for associations with HAV deformity and then compared the findings to a population with foot and gait abnormalities and a population known to be hypermobile. Past studies have tended to consider populations with HAV deformity and assess the level of generalised hypermobility in those groups. Carl suggested the need to measure ankle, subtalar and metatarsophalangeal joint movements (Carl et al., 1988). The assessment score used in this study included all lower limb joints and was therefore considered appropriate to use when investigating the relationship between HAV and lower limb hypermobility.

4.3 Method

Three groups of children were included in the study. Table 17 gives the basic demographic details. The first group consisted of children in primary classes at three West London schools. The second group included children attending the paediatrics clinic at the London Foot Hospital (LFH) with foot and gait problems of unknown cause at the time of referral. The third group consisted of children diagnosed with hypermobility from a specialist (rheumatologist, paediatrician) also attending the London Foot Hospital.

Table 17. Demographic data for the three groups of children

	Primary School Children	LFH Children	Referred with Hypermobility
Number	116	88	21
Mean Age (SD)	7.09 yrs (1.9)	9.89 yrs (3.39)	9.18 yrs (3.55)
Sex	66F : 50M	46F : 42M	13F : 8M

Children were excluded from the study when:

- A diagnosis of joint disease (ie. Juvenile Idiopathic Arthritis) existed that restricted normal joint motion.
- A current or previous orthopaedic injury / surgery (other than simple fracture) was present influencing normal movement.
- The child had a diagnosis of a neurological or neurodevelopmental disorder.

- Consent was not given by the parent or child.

Consent forms were sent to all parents of children attending the primary schools and requested basic demographic information including the child's age, sex and ethnic group. Incomplete forms were supplemented from school records. The children were assessed in a classroom environment within their schools.

Consent was obtained when the London Foot Hospital (LFH) children attended their clinical appointment and demographic information collected at that time.

All children were assessed using the Lower Limb Assessment Score (LLAS) (see figure 52) providing a score to a maximum of 12 marks for each limb. The Beighton score was taken for all primary school children and for a subgroup of LFH subjects providing a single score to a maximum of 9. Each child was also graded according to the clinical opinion of the assessor using three gradings: hypermobile, borderline hypermobile or normal.

The HAV angle was assessed with the child standing in their normal angle and base of gait, looking straight ahead. A finger goniometer was used to record the angle formed between the medial edge of the first metatarsal shaft and the medial edge of the proximal phalanx of the hallux (Kilmartin, 1988).

Ethical approval for the study was granted by Ealing NHS Hospital Trust Ethical Committee.

Figure 52. Lower Limb Assessment Score

LOWER LIMB HYPERMOBILITY ASSESSMENT FORM

Assessment Date: Assessors initials:

	LEFT	RIGHT
HIP FLEXION –the patient lies supine; the examiner flexes one hip fully; the other leg must stay fully extended on the couch. Does the mid-anterior area of the thigh drop easily onto the stomach/chest with a loose feel to the movement, using a minimum to moderate application of force?	YES NO	YES NO
HIP ABDUCTION-the patient lies supine, with hip and knees flexed to around 90°; the knees are dropped outwards and down to the couch, the soles of the feet remain together. With the examiner's hand against the lateral femoral condyle, can the knees come down to the couch sufficiently to let the back of the examiners hand touch the couch? - minimal application of force required.	YES NO	YES NO
KNEE HYPEREXTENSION-the patient lies supine; the knees are relaxed and straight; With minimal force, keeping the femoral condyles on the couch, can the heel be lifted at least 3cm off the couch (greater than 2 finger widths)?	YES NO	YES NO
KNEE ANTERIOR DRAW TEST-the patient is supine; the hips and knees are flexed; the examiner gently sits of the foot to stabilise it; moderate pressure is placed against the femoral condyles as the tibia is pulled forwards. Is there a definite, obvious forward movement of the tibia against the femur? Palpable "clunking" of the joint surfaces moving against each is indicative of a positive draw sign.	YES NO	YES NO
KNEE ROTATION – the patient lies supine; the examiner flexes the hip and knee to 90 degrees and palpates the tibial tubercle; holding the malleoli and ankle firmly, the tibia is rotated medially and laterally on the femur. Normal movement is 1cm medially and laterally. Does the tubercle move easily beyond 1cm in any direction or greater than 2cm overall? With increased internal movement the head of the fibula / lateral condyle of the tibia may also be seen to move.	YES NO	YES NO
ANKLE ANTERIOR DRAW TEST- the patient lies supine; the knee is flexed to 45 degrees; the examiner grasps the heel along the plantar and posterior surfaces with one hand and applied a stabilising force against the anterior of the tibia with the other hand. Using a strong anterior force, can the calcaneum and talus be brought forwards on the tibia? Any forwards movement felt is a positive result.	YES NO	YES NO

ANKLE JOINT DORSIFLEXION- the patient lies supine; the knee is flexed to 45 degrees; with moderate to strong force the ankle is dorsiflexed. Does the ankle flex more than 15 degrees? Along with the increased movement there may be bulging of the skin and subcutaneous fat anterior to the ankle.	**YES NO**	**YES NO**
SUBTALAR JOINT INVERSION-the patient is supine with their feet hanging off the end of the couch; the examiner holds the posterior surface of the heel and moves the heel into inversion without moving the leg. Is excessive inversion of the subtalar joint seen using minimal force? The sole of the foot or visualisation of the neck of the talus should show movement of 45 degrees inwards, the lateral head of the talus will be very prominent.	**YES NO**	**YES NO**
MIDTARSAL JOINT INVERSION-the patient is supine with their feet off the end of the couch; the heel is held still by the examiner grasping the posterior surface; the forefoot is grasped from lateral to medial along the metatarsal heads; only minimal - moderate force is applied to invert the midtarsal joint. Does the midtarsal joint invert beyond 45 degrees so that the plantar surface of the metatarsal heads can be brought inwards by 45 degrees?	**YES NO**	**YES NO**
MIDTARSAL JOINT AB/ADDUCTION AND DORSI/PLANTARFLEXION – the patient is supine with their feet off the end of the couch; the examiner grasps and stabilises the rearfoot; the forefoot is moved in the direction of ab/adduction and dorsi/plantarflexion. Normal movement should be 1cm in each direction. With minimal force, does the forefoot move easily, almost "wobbling", in an increased amount? Excessive movement in either of the two planes is a positive result.	**YES NO**	**YES NO**
METATARSOPHALANGEAL MOVEMENT - the patient is supine with their feet off the end of the couch; the hallux is dorsiflexed using minimal – moderate force. Does the hallux dorsiflex easily beyond 90 degrees relative to the metatarsal?	**YES NO**	**YES NO**
EXCESSIVE SUBTALAR JOINT PRONATION-the patient is to march on the spot and stop on command; the patient is asked to invert their foot and hold the position as subtalar joint neutral is found; the patient is then asked to relax their foot; the movement is observed. Does the arch lower and flatten fully, excessively and easily, with the talus bulging medially? The pronation noted should be at the end of range of the subtalar joint motion so that no further pronation is possible	**YES NO**	**YES NO**
	TOTAL:	
To score, each limb is calculated separately giving a left score and right score. Each YES is given one mark. A total of score of 12 marks is available.	**LEFT**	**RIGHT**

4.4 Data Analysis

All data was tested for normal distribution before statistical tests were applied.

◊ Frequency histograms allow for observation of the distribution and Q-Q plots were used to demonstrate whether the distribution of the variable matched a given distribution. If the selected variable matched the test distribution, the points would cluster around a straight line.

◊ The 1 sample Kolmogorov-Smirnov test was used to test the discrepancy between the set of values provided and the theoretical distribution. A probability value of $p<0.05$ was chosen to represent the level at which the hypothesis (the sample was drawn from a normal distribution) was rejected.

Parametric or non-parametric tests were applied depending upon the normality of the distribution.

◊ Scatter plots were used to assess the relationship between two variables. Correlation coefficients were determined to measure the strength of the association.

◊ Reliability analysis was undertaken to determine the agreement between raters. Intraclass correlation coefficients (ICC) were determined. A two-way mixed effects model was used when the subjects were randomly chosen but the raters were not. Absolute agreement definition was applied to assess for systematic differences among the raters. Cohen's kappa was used to determine levels of agreement between ordinal data (where κ = 0.41 to 0.6 indicates moderate agreement, κ = 0.61 to 0.8 indicates substantial agreement and κ = 0.81 to 1.0 indicates almost perfect agreement).

◊ Ordinal data (eg. LLAS 0-12 or clinical diagnosis - hypermobile, borderline, normal) was tested with non-parametric tests. The distribution of single data were compared with a Chi squared test. Paired data were tested using the Wilcoxon matched pairs signed ranks test.

◊ Dichotomous data (eg. yes/no, 0/1) were tested with Chi squared test for single data or McNemar test for paired data.

◊ The Student t-test was applied to parametric data to test for differences between two variables, applying independent sample t-tests or paired t-tests where appropriate. The Mann-Whitney test was used as the non-parametric alternative.

◊ The Kruskal-Wallis test was used as the non-parametric alternative when the data was ordinal or dichotomous and a one-way ANOVA was used for continuos data to test for associations between three or more groups.

◊ For testing the diagnostic capabilities of the scoring system, the sensitivity and specificity were determined:

Sensitivity = number of true positive cases/(number of true positive + false negative)

Specificity = number of true negative cases/(number of true negative + false positive)

A receiver operating characteristic (ROC) curve was produced to demonstrate the optimal threshold of the scoring system.

◊ Positive predictive values (PPV) and negative predictive values (NPV) were calculated for the identified threshold.

PPV = number of true positive cases / (number of true positive + false positive)

NPV = number of true negative cases / (number of true negative + false negative)

◊ Cluster analysis was used to explore the data for associations between variables in the lower limb assessment score.

A probability level of $p<0.05$ was chosen to represent the level at which statistical significance was reached for all tests.

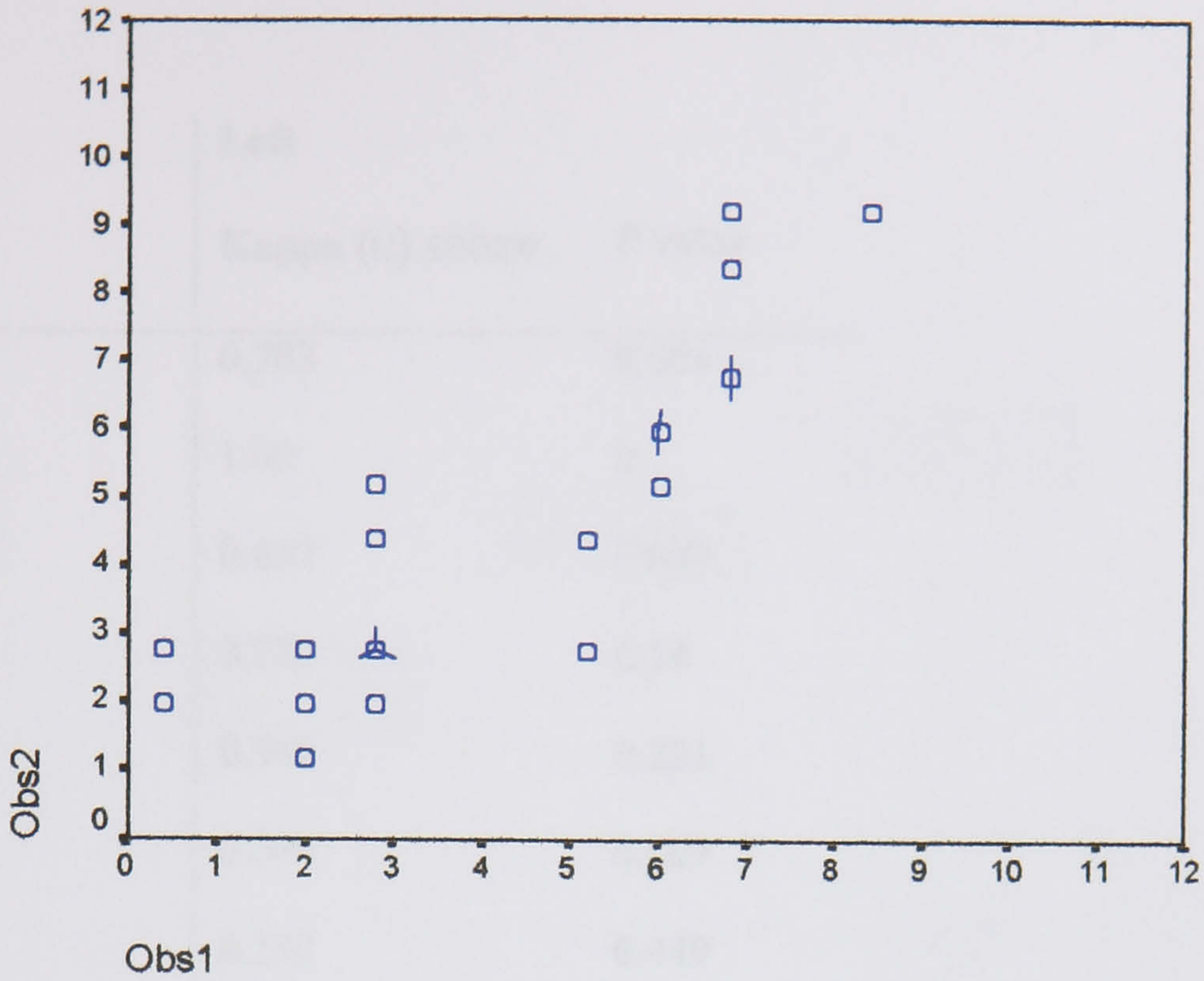
4.5 Results

4.51 Repeatability of Lower Limb Assessment Score

Twenty-two children were measured by two observers. The scatter plot (figure 53) suggests that there was good agreement between the observers.

The relationship between the observers' score was tested using reliability analysis. The intraclass correlation coefficients for the two observers was ICC = 0.84 (95% CI = 0.62 to 0.93), ($F(1,21) = 6.08$, $p = 0.001$). This was the same for left and right sides.

Figure 53. Scatter plot of observers' scores for left side measurements



In order to test the difference between the observers' clinical opinion, the three observations (hypermobile, borderline hypermobility, normal) were considered as ordinal data and a Wilcoxon matched pairs Signed Ranks test was applied. There was no significant difference between observers for the clinical diagnoses for left or right feet ($z = 0.221$, $p \geq 0.33$).

Assessment of the scores given for each individual joint movement in the scoring system (1 = hypermobile, 0 = normal) showed that the agreement between the observers varied for each joint movement. The McNemar test for dichotomous data was used to test whether the agreement between the observers was significantly different. No significance difference was found for any movement ($p \geq 0.13$).

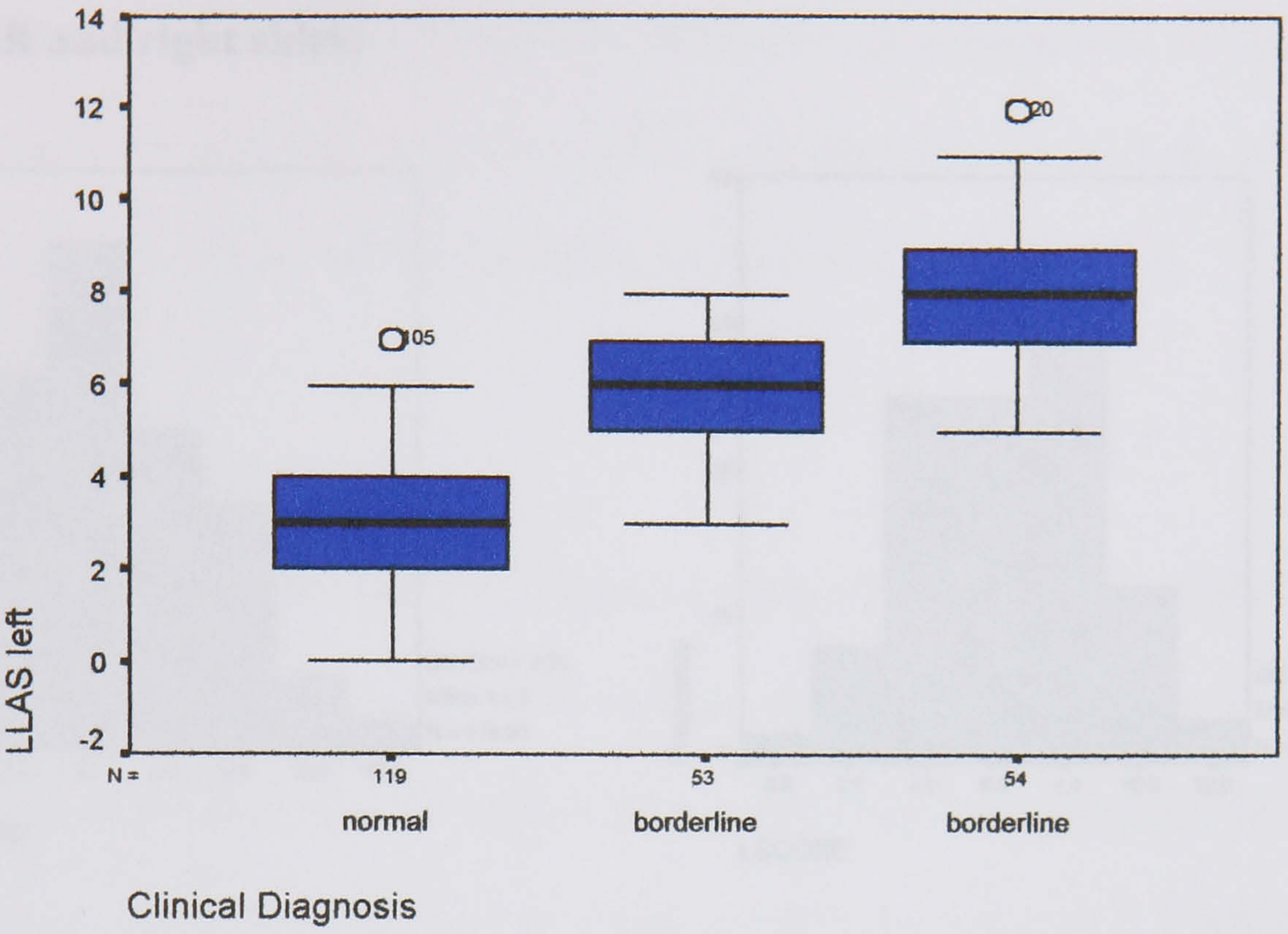
Table 18 shows the levels of agreement for each joint (left side) expressed by the kappa score.

Table 18. Showing levels of agreement between the observers for each joint assessed and significance level.

	Left	
	Kappa (κ) score	**P value**
Hip flexion	0.703	0.001
Hip abduction	1.00	0
Knee hyperextension	0.637	0.003
Knee draw	0.522	0.14
Knee rotation	0.241	0.221
Ankle dorsiflexion	0.546	0.009
Ankle draw	0.132	0.449
Subtalar joint inversion	0.389	0.068
Midtarsal joint inversion	0.441	0.035
Midtarsal joint abd/adduction	0.233	0.259
1st mtpj dorsiflexion	0.53	0.01
Excessive subtalar pronation	0.582	0.006

The association between the LLAS and the clinical diagnosis was investigated. Figure 54 suggests that an association was present. This was confirmed using Kruskal-Wallis test. The left side and right sides showed a significant difference between the LLAS and clinical diagnosis (X^2= 164.92, df = 2, p < 0.001).

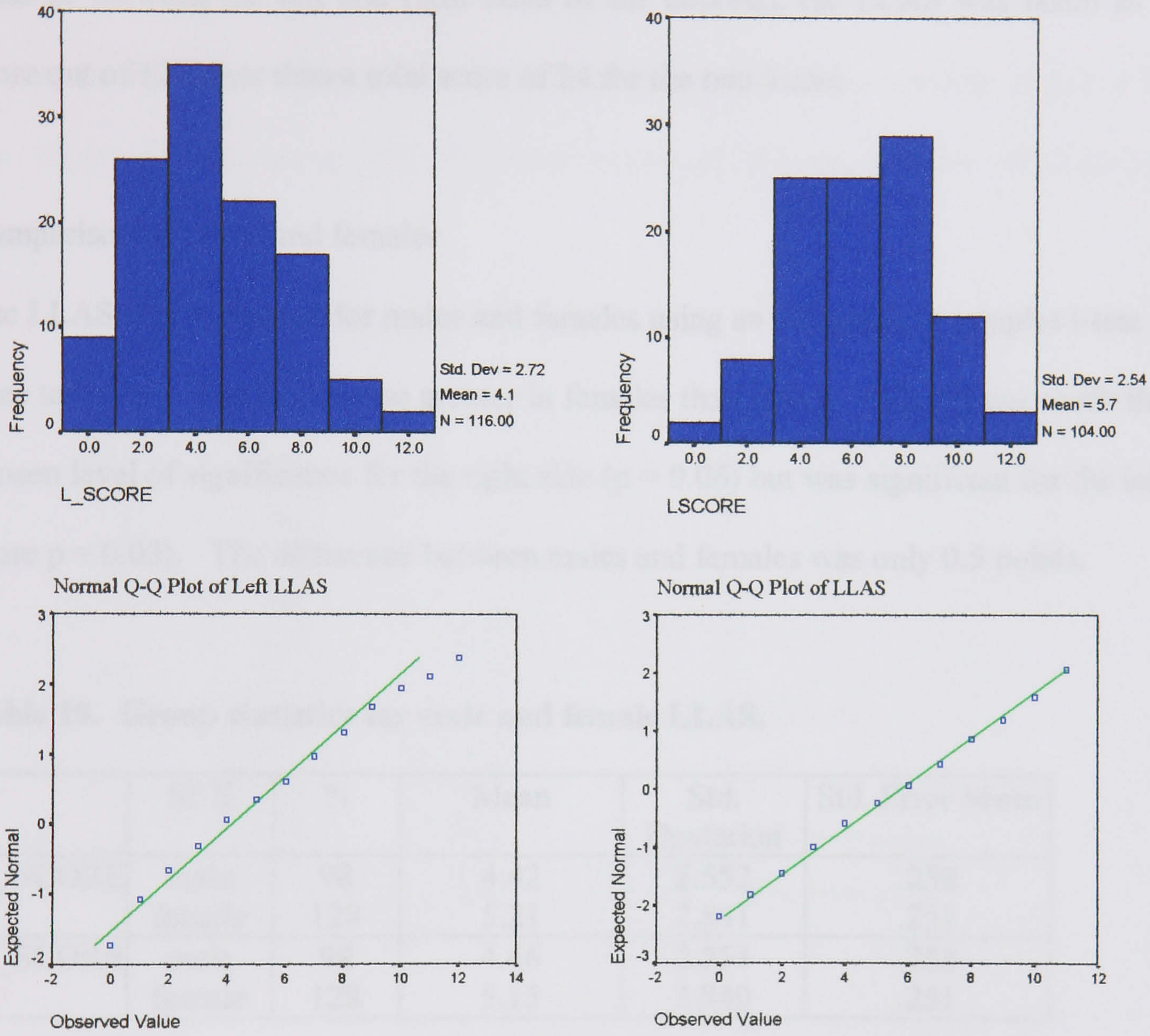
Figure 54. Differences between the assessment scores for each clinical diagnosis (left side).



Comparison of left to right sides

A total of 116 primary school children were assessed. The normality of the distribution of the lower limb assessment score was tested using a 1 sample Kolmogorov-Smirnov test. Both left and right side scores were normally distributed ($p = 0.06$ and $p = 0.07$ respectively) (see figure 55).

Figure 55. Frequency Histogram of LLAS and normality plot for primary school children (left and right sides)



A total of 110 children were assessed at the London Foot Hospital. The scores for left and right sides were also normally distributed (p=0.14 and p=0.2 respectively)

The data was combined initially (n = 226). The LLAS for the left and right sides was compared using a paired t-test. There was no significant difference between the left side (mean = 4.87, SD = 2.7, SE = 0.18) and right side (mean = 4.85, SD = 2.7, SE = 0.18) for the lower limb assessment score (p = 0.74).

Since there was no difference between the observers measurement of left and right sides or between the left and right sides of the children, the LLAS was taken as a score out of 12 rather than a total score of 24 for the two limbs.

Comparison of males and females

The LLAS was compared for males and females using an independent samples t-test (see table 19). The LLAS was greater in females than males – this did not reach the chosen level of significance for the right side (p = 0.06) but was significant for the left score p = 0.03). The difference between males and females was only 0.5 points.

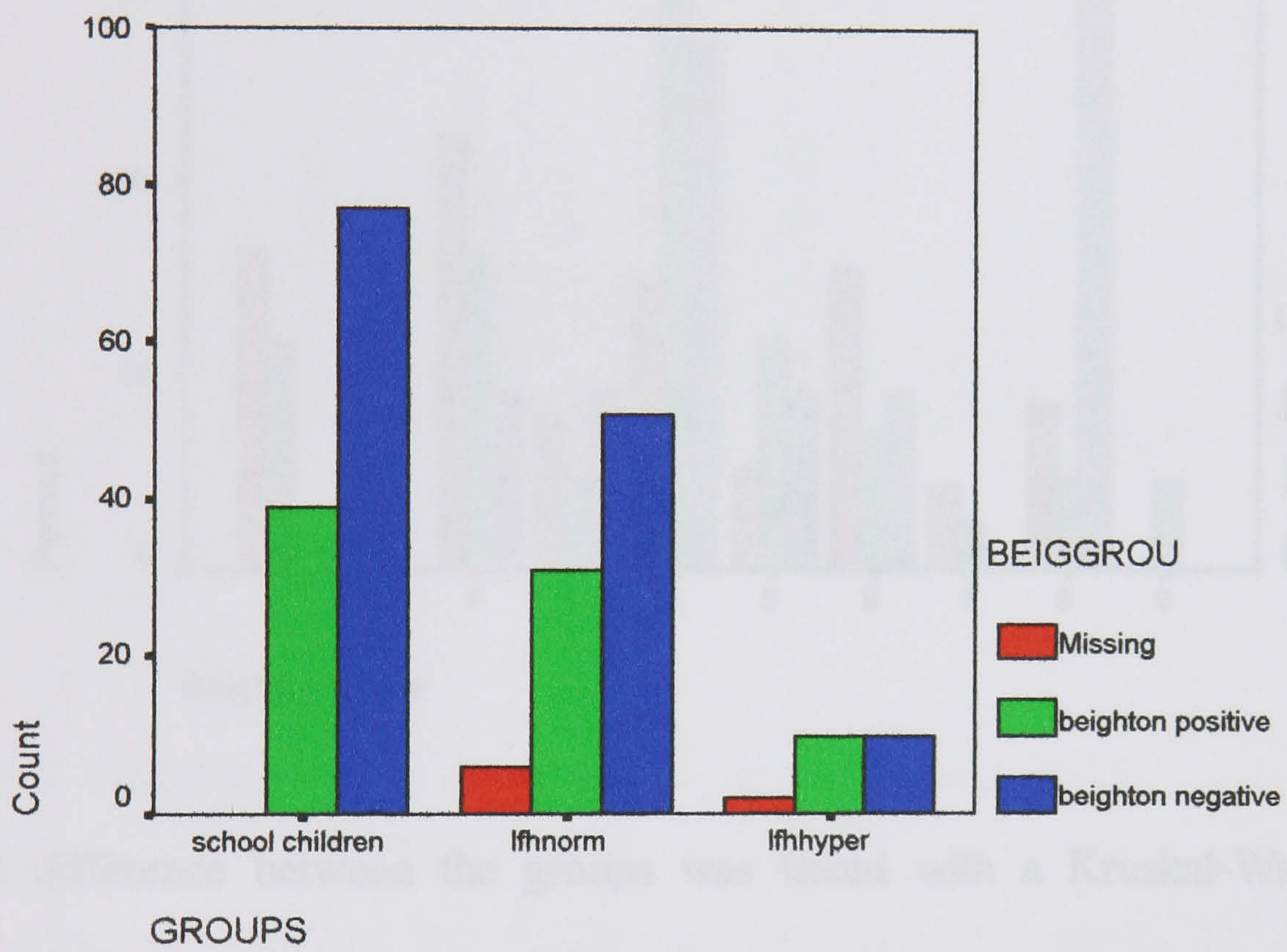
Table 19. Group statistics for male and female LLAS.

	SEX	N	Mean	Std. Deviation	Std. Error Mean
L_SCORE	male	98	4.42	2.552	.258
	female	128	5.21	2.841	.251
R_SCORE	male	98	4.46	2.553	.258
	female	128	5.15	2.840	.251

4.52 Considering the Beighton score and Lower Limb Assessment Score to measure hypermobility

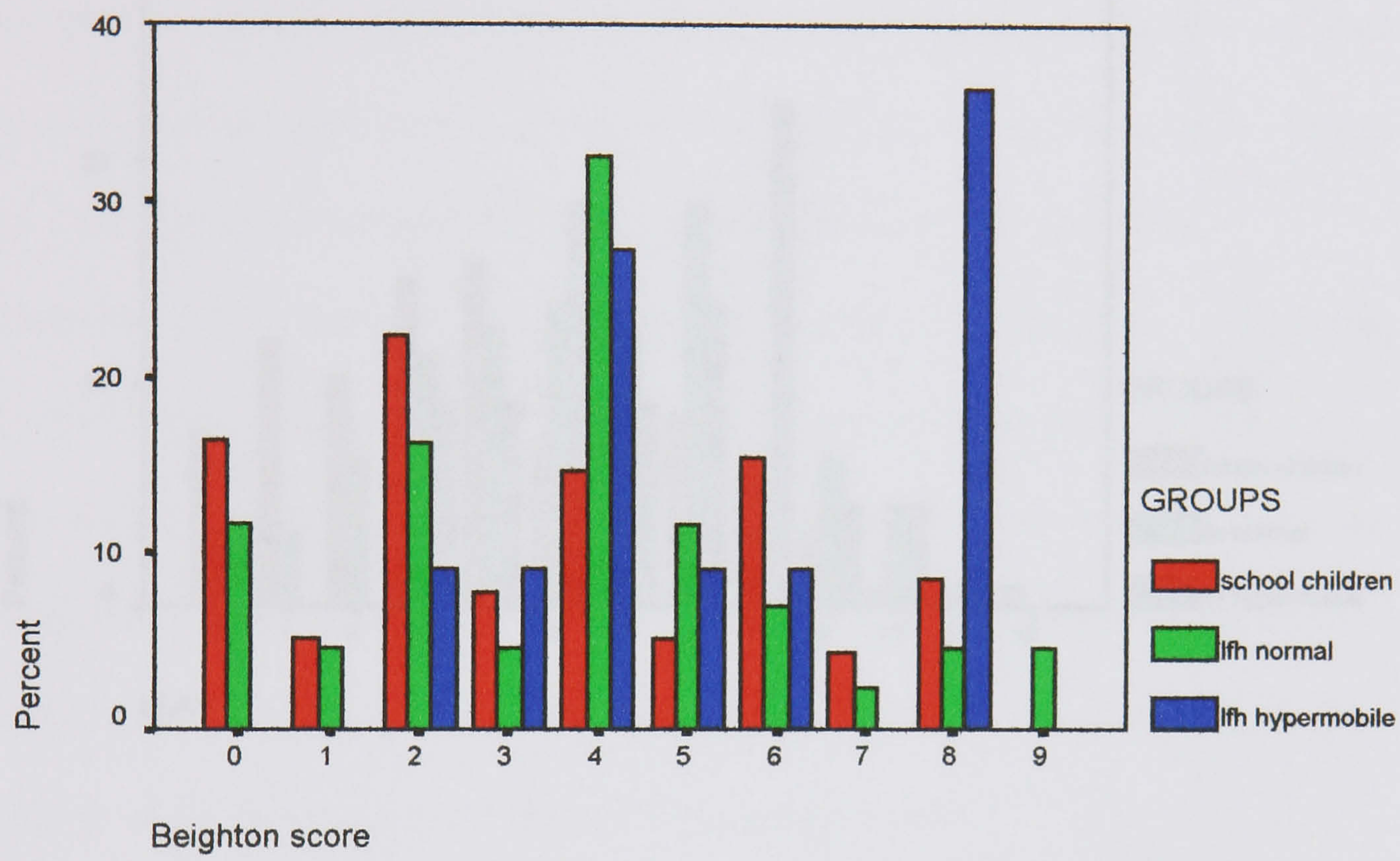
The number of children found to be hypermobile using the Beighton score was compared in the three groups. Figure 56 shows the numbers of children diagnosed as being hypermobile (Beighton positive = 5/9 or greater) or not hypermobile (Beighton negative). Within the school children, 39 children (45%, 95% CI = 27 to 51%) were found to be hypermobile using this criterion for hypermobility. In the group referred from a specialist as hypermobile, 11 children (60%, 95% CI = 31 to 74%) were Beighton positive whilst 31 children (35%, 95% CI = 25 to 45%) of the group with foot and gait problems were found to be hypermobile.

Figure 56 showing distribution of hypermobile and not hypermobile children in the three groups using the Beighton score of 5/9 or greater to indicate hypermobility.



The group referred from a specialist were expected to have higher Beighton scores than the other two groups. The percentage of children for each level of the Beighton score was considered in order to test whether the Beighton score could differentiate between the three groups of children. Observation of figure 57 suggested that the Beighton score was not able to clearly differentiate between the groups, except at the higher scores where the percentage of children increased in the hypermobile group and decreased in the other two groups. The score of 8/9 appeared to discriminate best between the groups.

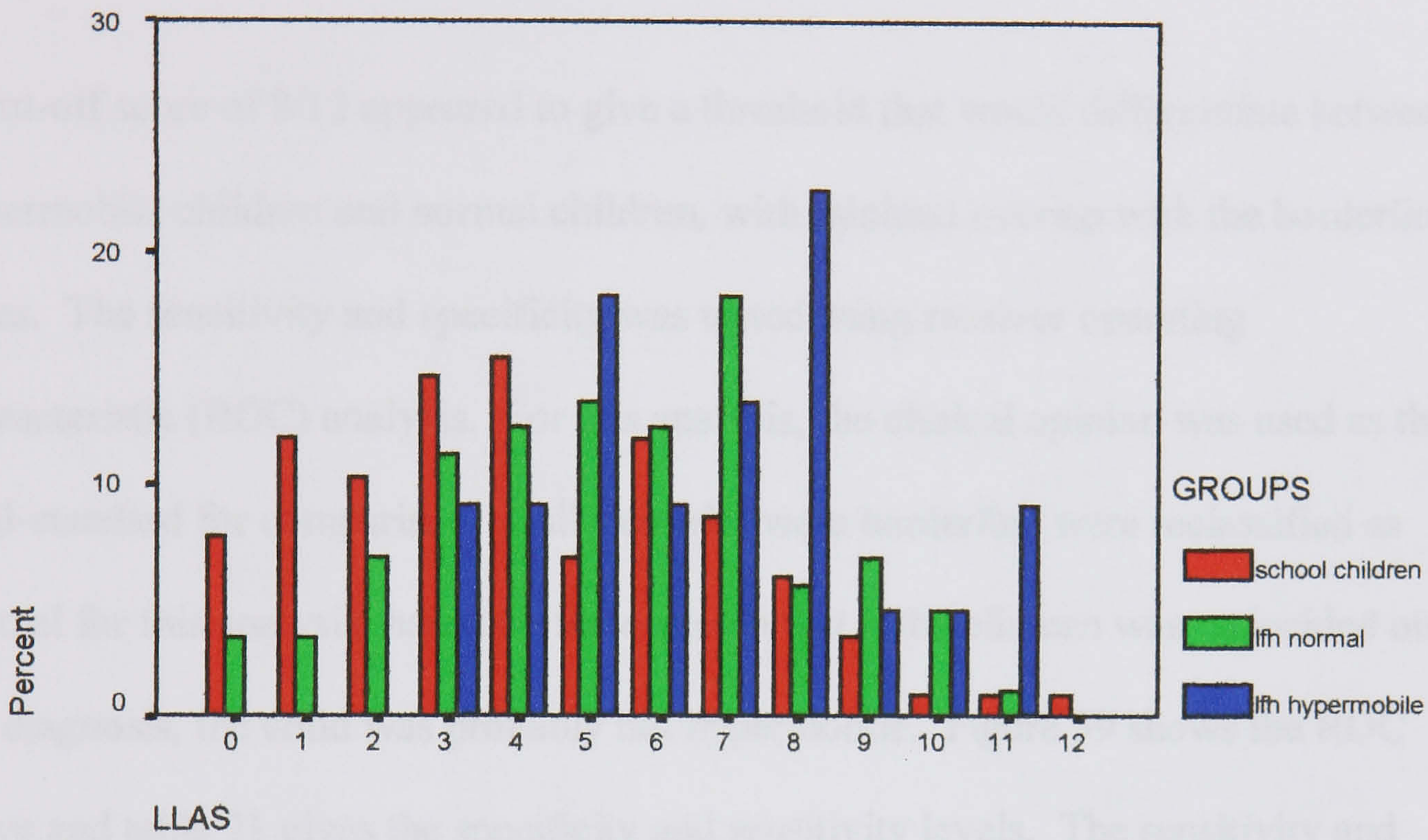
Figure 57. Bar Chart showing Beighton scores in three groups of children



The difference between the groups was tested with a Kruskal-Wallis test. The probability value obtained suggested that the difference between the groups was just on the level of significance ($X^2 = 5.87$, df $= 2$, $p = 0.053$).

The LLAS was investigated in the same way. Observation of figure 58 suggested that the LLAS was able to distinguish between the groups more clearly, with a noticeable difference in the distribution of the scores for school children and those referred from a specialist. The distinction was seen at a lower level of the score (5/12). A Kruskal-Wallis test was used to test the observation that there was a difference in the LLAS scores. A significant difference was seen between the groups ($X = 21.52$, $df = 2$, $p < 0.001$).

Figure 58. Bar Chart showing the Lower Limb Assessment Score for the three groups.



4.53 Defining a cut-off score for hypermobility in the LLAS

In order to consider the number of children that would be diagnosed with hypermobility in the primary school group using the LLAS, a cut-off point to define hypermobility had to be set. All children were assessed for the clinical opinion of the examiner as to whether they were hypermobile, borderline hypermobility or normal. Table 20 shows the mean values for the LLAS in each group. Figure 54 expressed these mean values graphically.

Table 20 showing Lower Limb Assessment Scores for each clinical diagnosis (left side)

	Assessment Score		
	Mean	SD	Range
hypermobile	8.35	1.44	6-12
borderline	5.87	1.06	3-8
normal	2.84	1.66	0-7

A cut-off score of 8/12 appeared to give a threshold that would differentiate between hypermobile children and normal children, with minimal overlap with the borderline cases. The sensitivity and specificity was tested using receiver operating characteristic (ROC) analysis. For this analysis, the clinical opinion was used as the gold-standard for comparison. Children who were borderline were reclassified as normal for this analysis, based on the decision that if the clinican was undecided on the diagnosis, the child was probably not hypermobile. Figure 59 shows the ROC curve and table 21 gives the specificity and sensitivity levels. The sensitivity and specificity of the Beighton score is shown for comparison.

Table 21. True positive and false positive rates for diagnosing hypermobility with the LLAS.

Lower Limb Assessment Score			Beighton Score		
Cut-off point	**Sensitivity**	**1-specificity**	**Cut-off point**	**Sensitivity**	**1-specificity**
0	1.000	0.765	**0**	**1.000**	**1.000**
1	1.000	0.712	**1**	**1.000**	**0.844**
2	1.000	0.637	**2**	**0.981**	**0.762**
3	1.000	0.558	**3**	**0.885**	**0.514**
4	1.000	0.429	**4**	**0.865**	**0.425**
5	1.000	0.292	**5**	**0.769**	**0.237**
6	0.981	0.186	**6**	**0.673**	**0.169**
8	0.943	0.075	**7**	**0.365**	**0.031**
8	0.704	0.004	**8**	**0.212**	**0.019**
9	0.407	0.000	**9**	**0.035**	**0.006**
10	0.169	0.000			
11	0.058	0.000			
12	0.014	0.000			

Table 21 shows how at the threshold of LLAS=6/12, the sensitivity begins to decrease, so that some children considered to be hypermobile clinically are missed. The number of false events (children not hypermobile but then classified as hypermobile) is still relativity large (0.186 or 18.6%). At the threshold of LLAS=7/12, the sensitivity is still good at 94% and the false positive rate has improved to 7.5%. At the threshold of LLAS=8/12, the sensitivity has decreased to 0.704 (70.4%) but the false positive rate is extremely good at 0.4%.

Figure 59 showing ROC curve for the Lower Limb Assessment Score and Beighton score

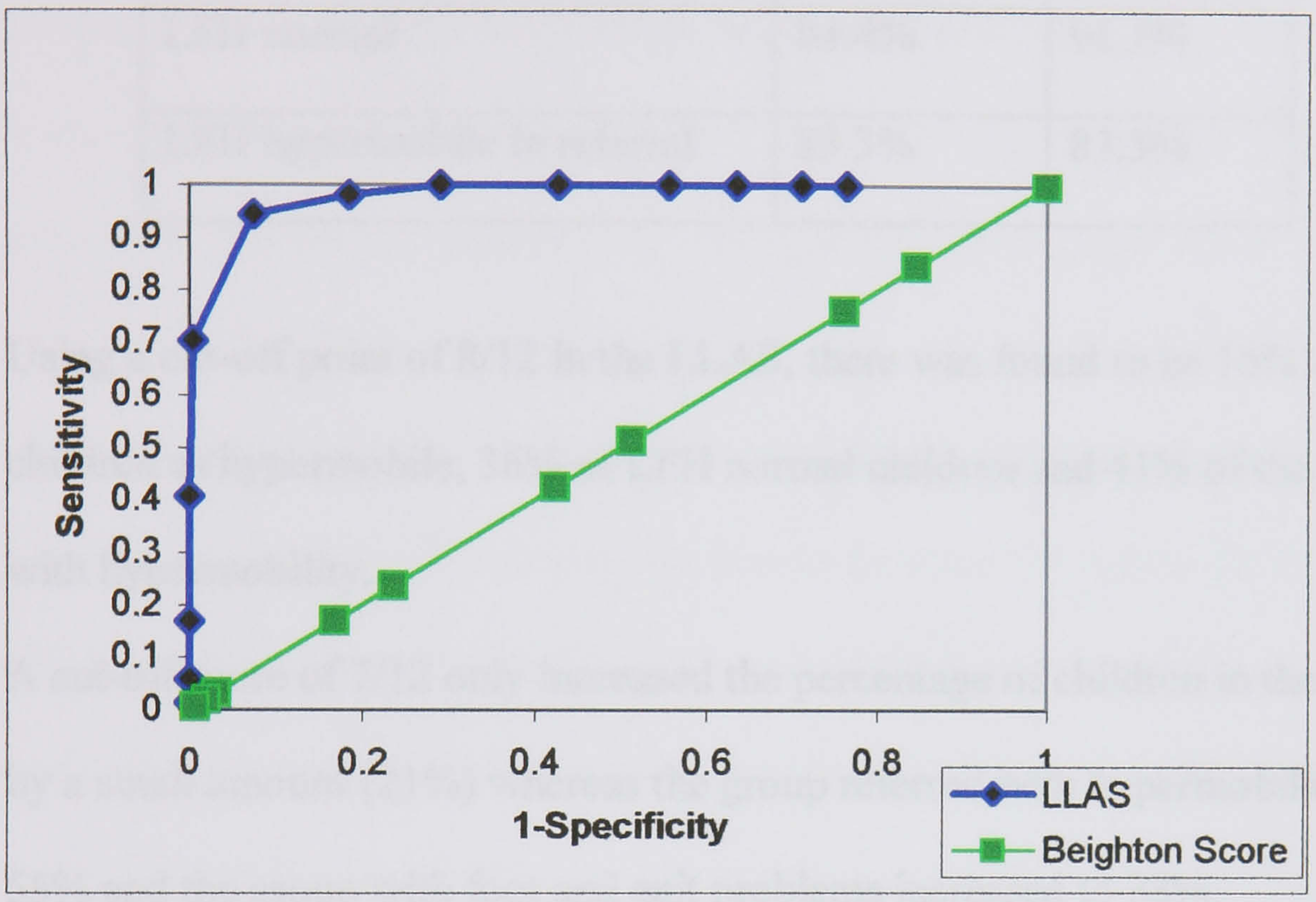


Figure 59 shows the ROC curve for both tests. The curve shows the trade-off between sensitivity and specificity with the curve closest to the left-hand and top borders being the most accurate. The point on the ROC curve closest to both axes represents the most useful score in terms of sensitivity and specificity. On the LLAS this point is the score of 7/12.

The positive predictive values (PPV) and negative predictive values (NPV) were considered in each group of children for the threshold of 7/12 defining hypermobility. The PPV tests the probability that the subject has the disease, when restricted to those subjects who do have the disease. Table 22 shows the values for each group.

Table 22. Positive predictive values (PPV) and negative predictive values (NPV) for the three groups of children, taken at hypermobility = LLAS of 7/12 or greater.

	PPV	NPV
School children	58.3%	89.1%
LFH normal	84.4%	91.5%
LFH hypermobile in referral	83.3%	83.3%

Using a cut-off point of 8/12 in the LLAS, there was found to be 16% of school children as hypermobile, 36% of LFH normal children and 41% of the group referred with hypermobility.

A cut-off score of 7/12 only increased the percentage of children in the school group by a small amount (21%) whereas the group referred with hypermobility increased to 55% and the group with foot and gait problems increased to 38%.

Table 23 shows the percentage children in each group using each cut-off point.

Table 23. Percentage of children found to be hypermobile with two cut-off points.

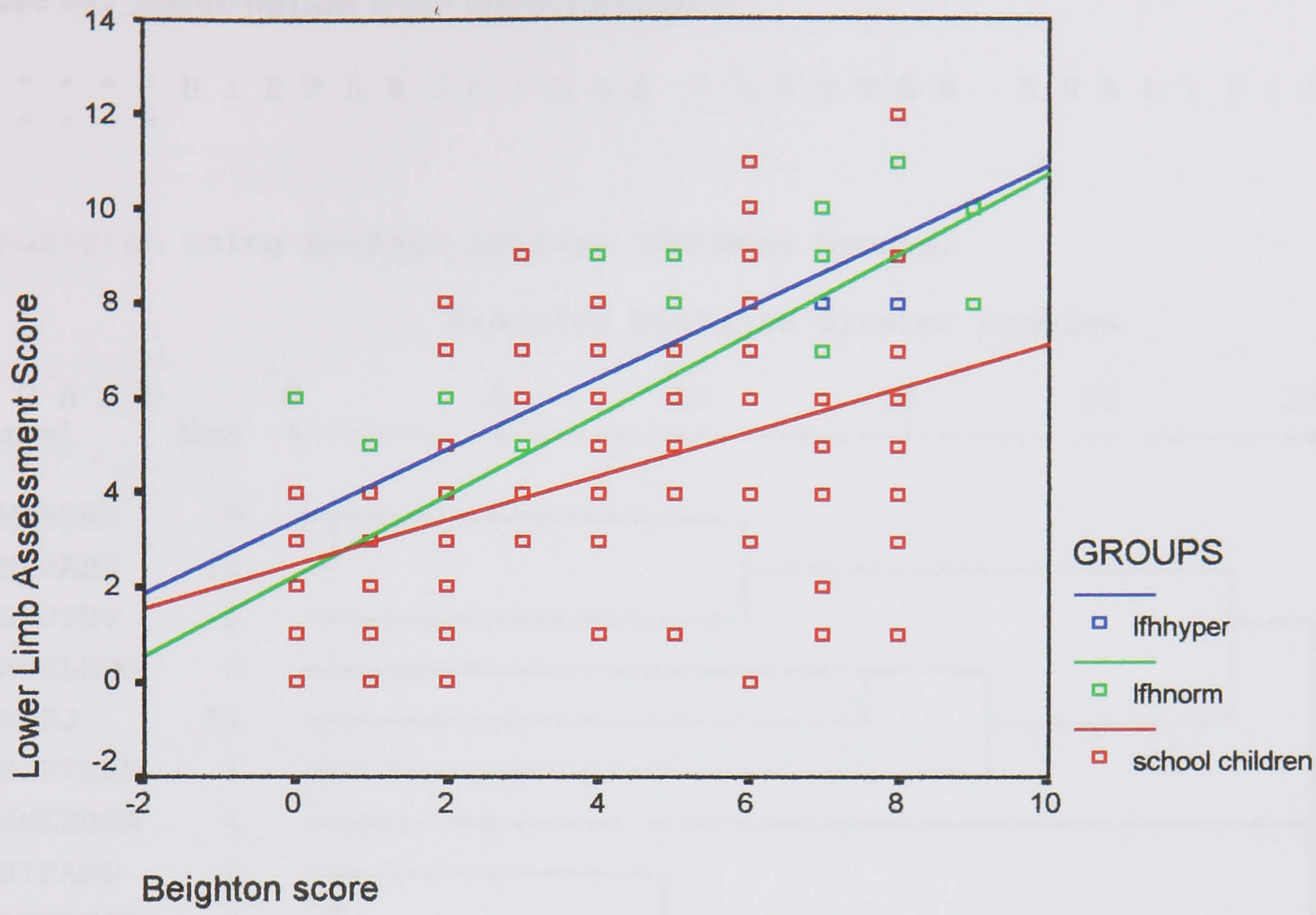
	Percentage hypermobile	
	Cut-off = 7/12	Cut-off = 8/12
School children	21% (95% CI = 11 to 25%)	16% (95% CI = 10 to 23%)
LFH normals	36% (95% CI = 26 to 46%)	38% (95% CI = 27 to 48%)
LFH hypermobile in referral	52% (95% CI = 31 to 74%)	41% (95% CI = 21 to 64%)

In the group referred with a diagnosis of hypermobility, there was agreement between the LLAS (>7/12) and the Beighton score (>5/9) in 80% of cases. In 2 children (10%), the LLAS indicated hypermobility, but the Beighton score was less than 5/9. In 2 cases the Beighton score indicated hypermobility, but the LLAS did not.

In the school children, there was agreement in 69% of cases. In 31 cases (26.7%), the Beighton score suggested the child was hypermobile but the LLAS suggested the lower limb was not hypermobile. In 5 cases (4.3%), lower limb hypermobility was found that was not accompanied by a Beighton score of greater than 5/9.

The association between the Beighton score and LLAS was tested with Pearson's correlation. A weak relationship was shown between the scores for the school children ($r = 0.43$, $p < 0.01$) but a stronger relationship existed for the group with foot and gait problems ($r = 0.69$, $p < 0.01$) and the group referred with hypermobility ($r = 0.69$, $p = 0.018$). Figure 60 demonstrates the relationship between the LLAS and Beighton score for each group.

Figure 60 showing relationship between the Lower Limb Assessment Score and Beighton score for groups.

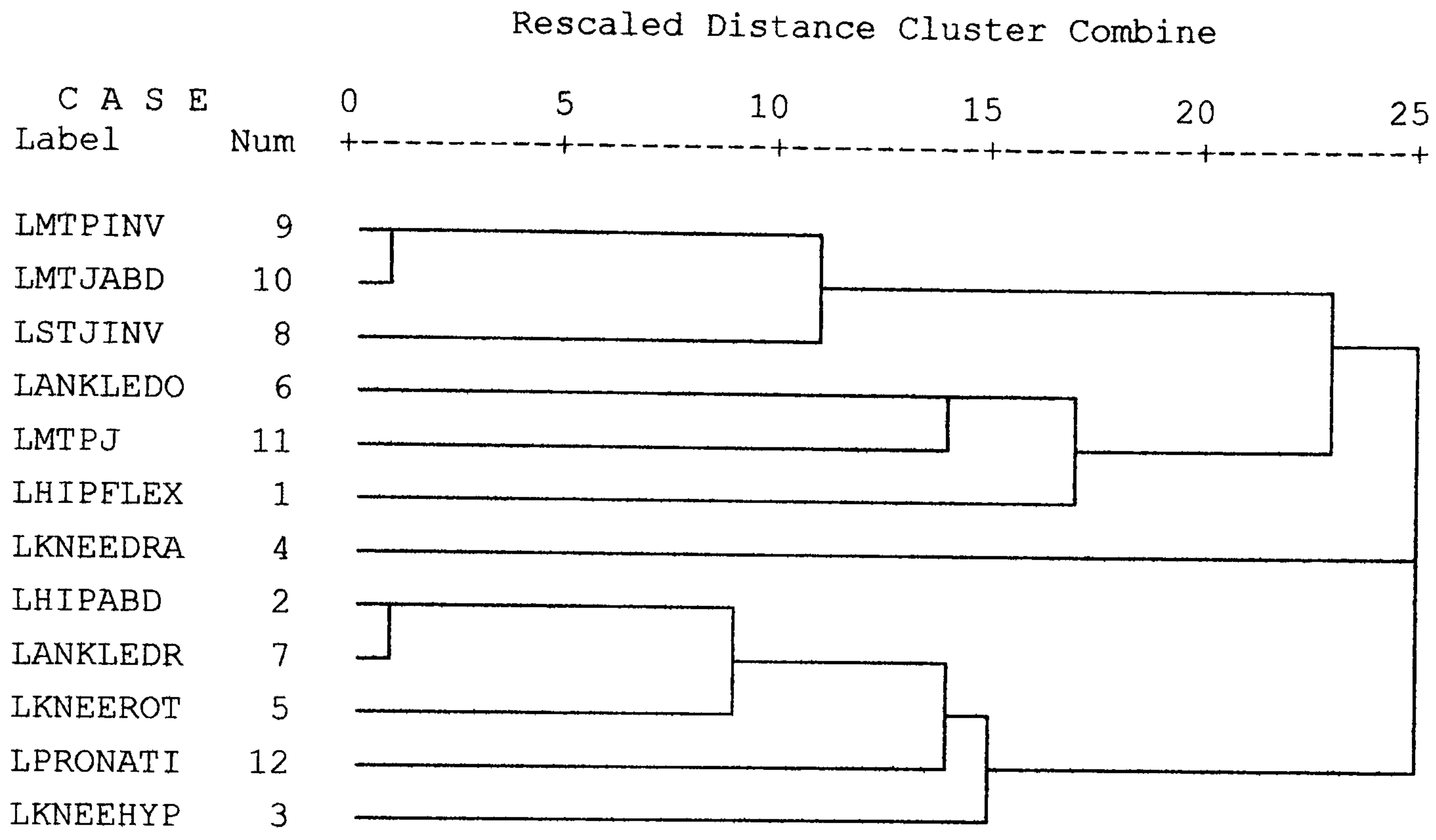


Cluster analysis was undertaken to determine if any of the joint movements within the score were related to each other. Figure 61 shows the dendrogram formed from the analysis. No obvious groupings of the joint movements could be identified.

Figure 61. Dendrogram from cluster analysis

* * * * * * H I E R A R C H I C A L   C L U S T E R   A N A L Y S I S * * * * * *

Dendrogram using Average Linkage (Between Groups)



4.54 The LLAS vs the Beighton score – other associations

The association with age was tested given that hypermobility is expected to reduce with increasing age. An association was found in the group with foot and gait problems for both scores but only with the LLAS in the school children. The association showed a trend towards decreasing flexibility with increasing age. No such trend was shown in the hypermobile group (table 24).

Table 24 showing Pearson correlation for the scoring systems versus age

	Beighton score	LLAS
School children	r = - 0.12, p = 0.18	r = -0.21, p = 0.024
Group with foot and gait problems	r = -0.36, p = 0.017	r = -0.46, p = 0.017
Group referred with hypermobility	r = -0.27, p = 0.42	r = -0.19, p = 0.40

The differences in the ethnicity of the groups were considered. Figure 62 and 63 shows that the primary school children were from a predominantly Asian background whilst the LFH groups (combined) were from a generally Caucasian background..

Figure 62. Pie chart representing the ethnic background of the primary school children.

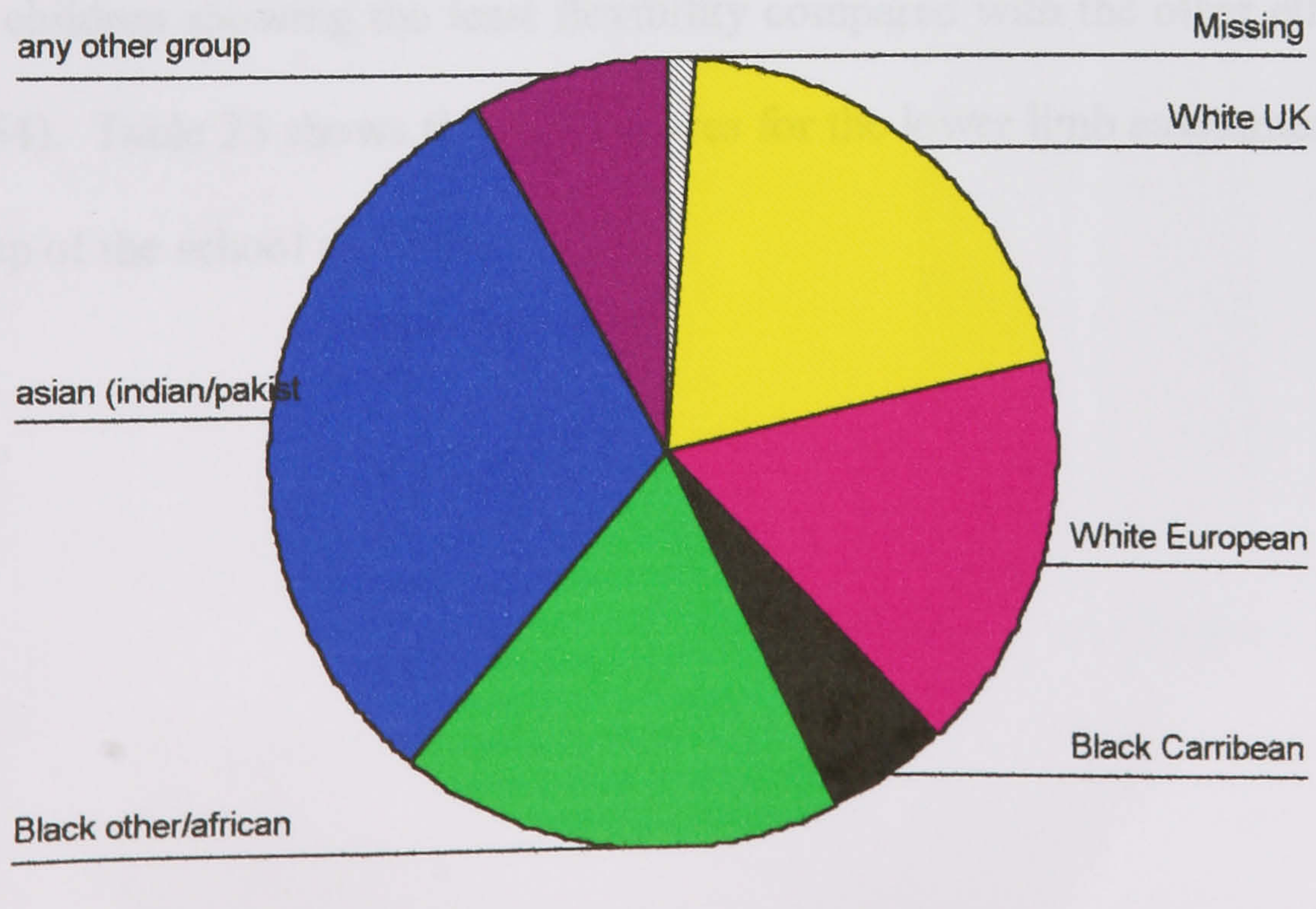
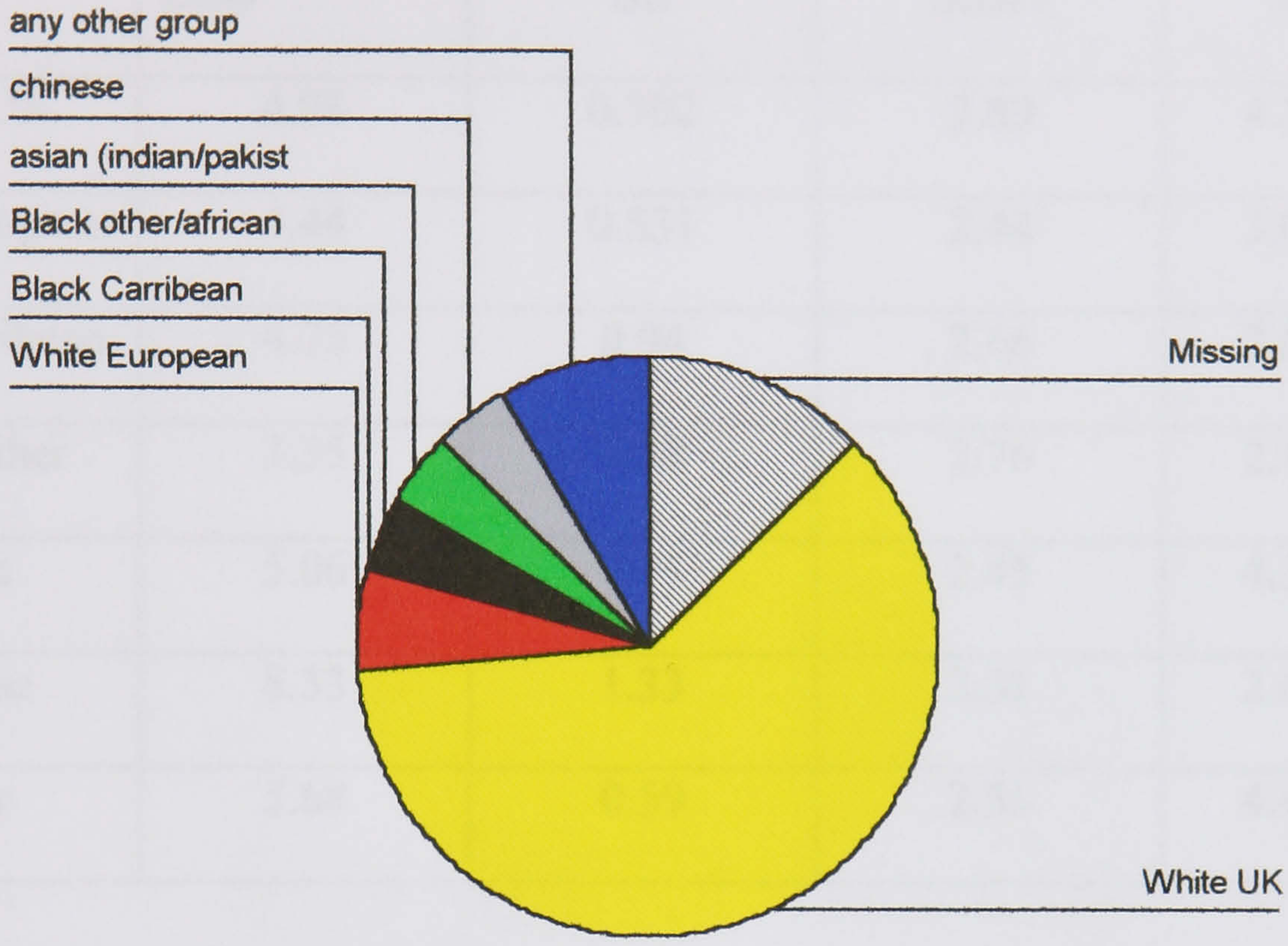


Figure 63. Pie chart showing ethnic background of LFH children

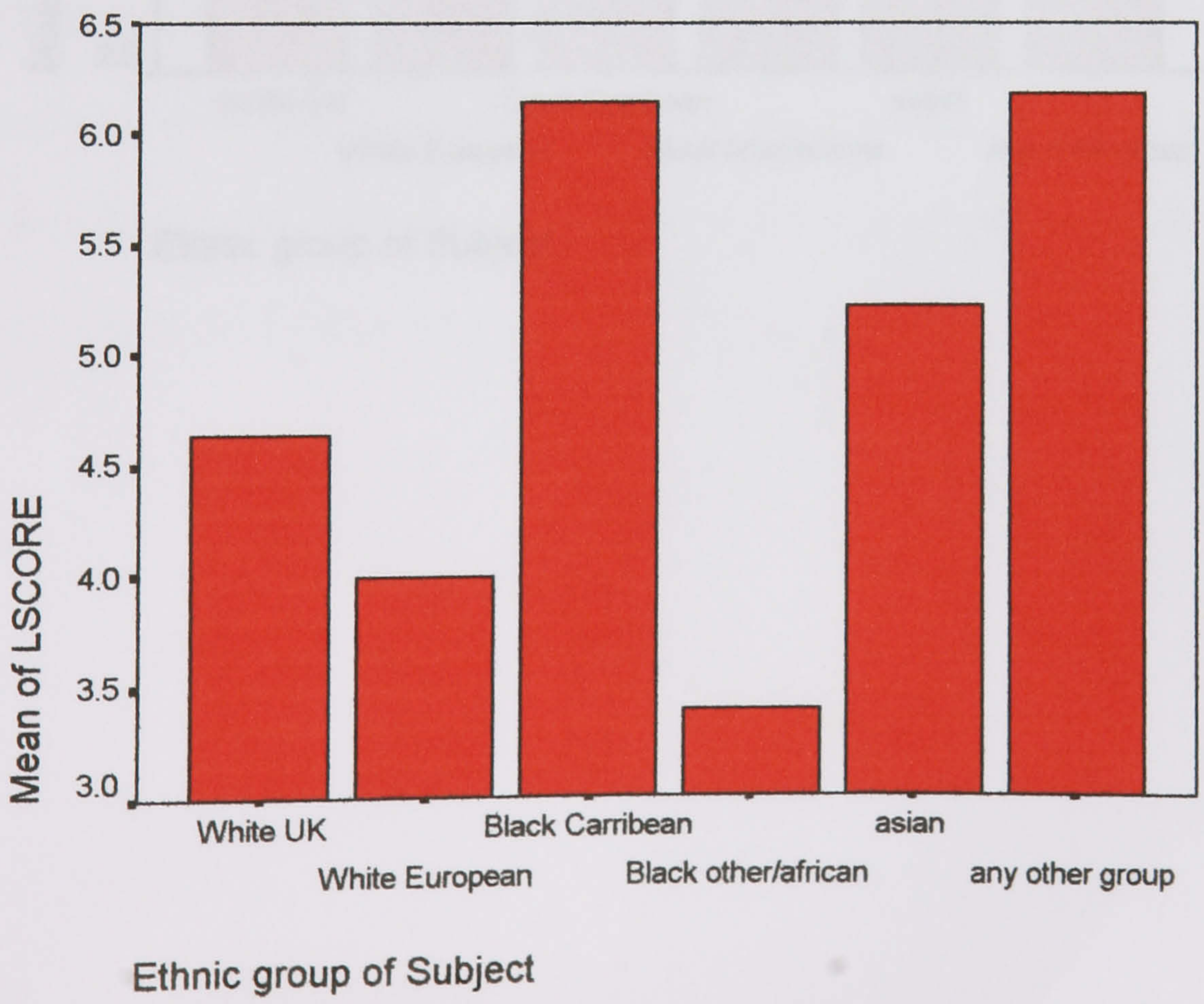


The relationship between the LLAS and the ethnic group was tested for all the children combined (data was missing for 61 children). A significant difference was found between the LLAS and the ethnic group ($F(5,160) = 2.94$, $p=0.015$) with white UK children showing the least flexibility compared with the other ethnic groups (see fig 64). Table 25 shows the mean scores for the lower limb assessment in each ethnic group of the school children.

Table 25. Showing LLAS (right side) for ethnic groups in primary school

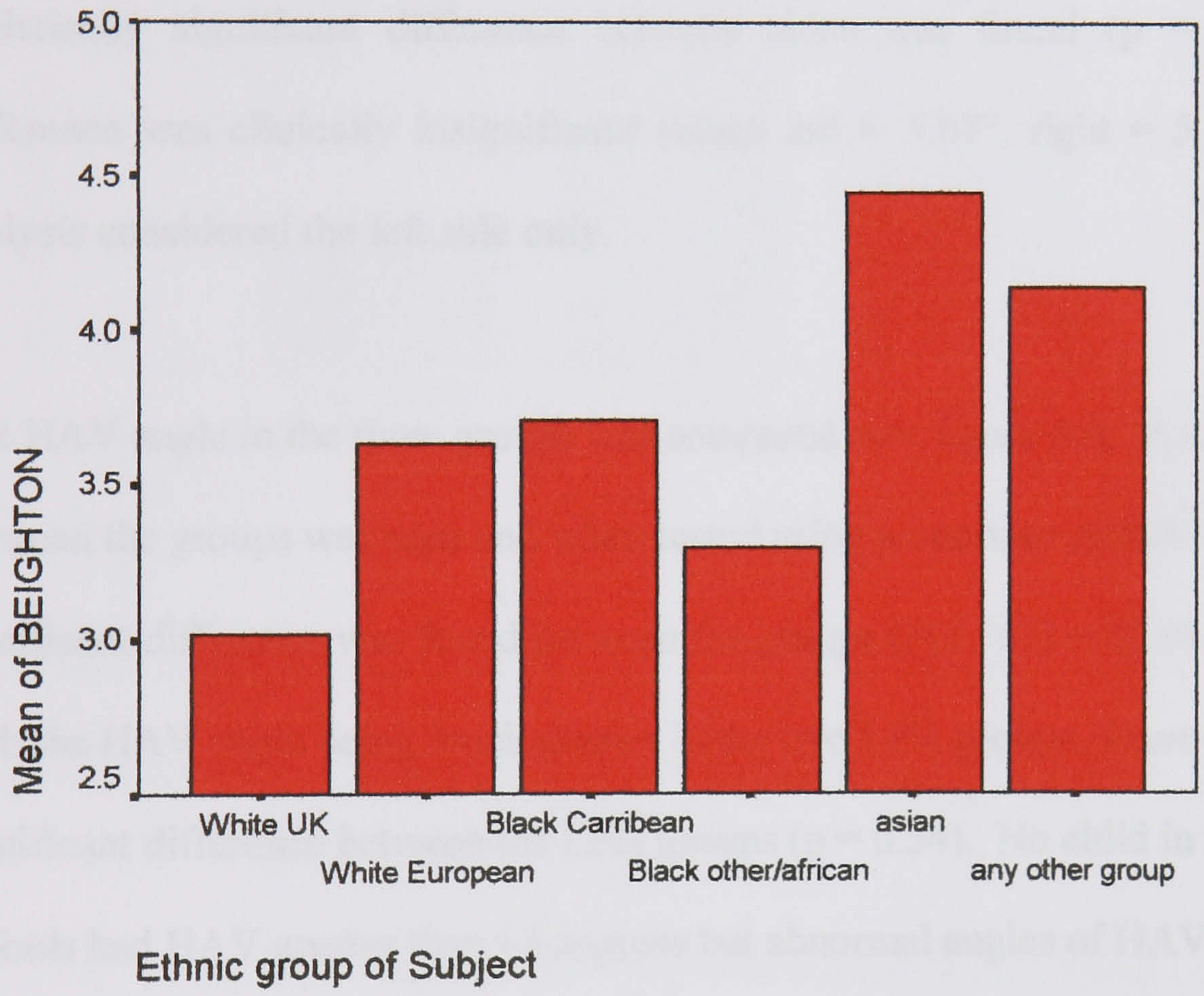
	Mean	SE	StDev	95%CI
White UK	4.98	0.302	2.89	4.38-5.58
White european	4.44	0.531	2.44	3.03-5.25
Black Caribean	4.75	0.94	2.66	2.53-6.97
Black other	3.35	0.58	2.76	2.16-4.54
Asian	5.06	0.36	2.45	4.34-5.78
Chinese	8.33	1.33	2.31	2.6-14.07
Other	5.68	0.59	2.56	4.45-6.92

Figure 64 showing bar chart of mean LLAS for each ethnic group in study



The relationship between the Beighton score and ethnic group was tested using a one-way ANOVA. Figure 65 shows the plot of mean scores for each ethnic group. No difference between the groups was found ($F(5,142) = 1.66$, $p = 0.14$) despite the increased score in the Asian group.

Figure 65 showing bar chart of mean Beighton score for each ethnic group in study



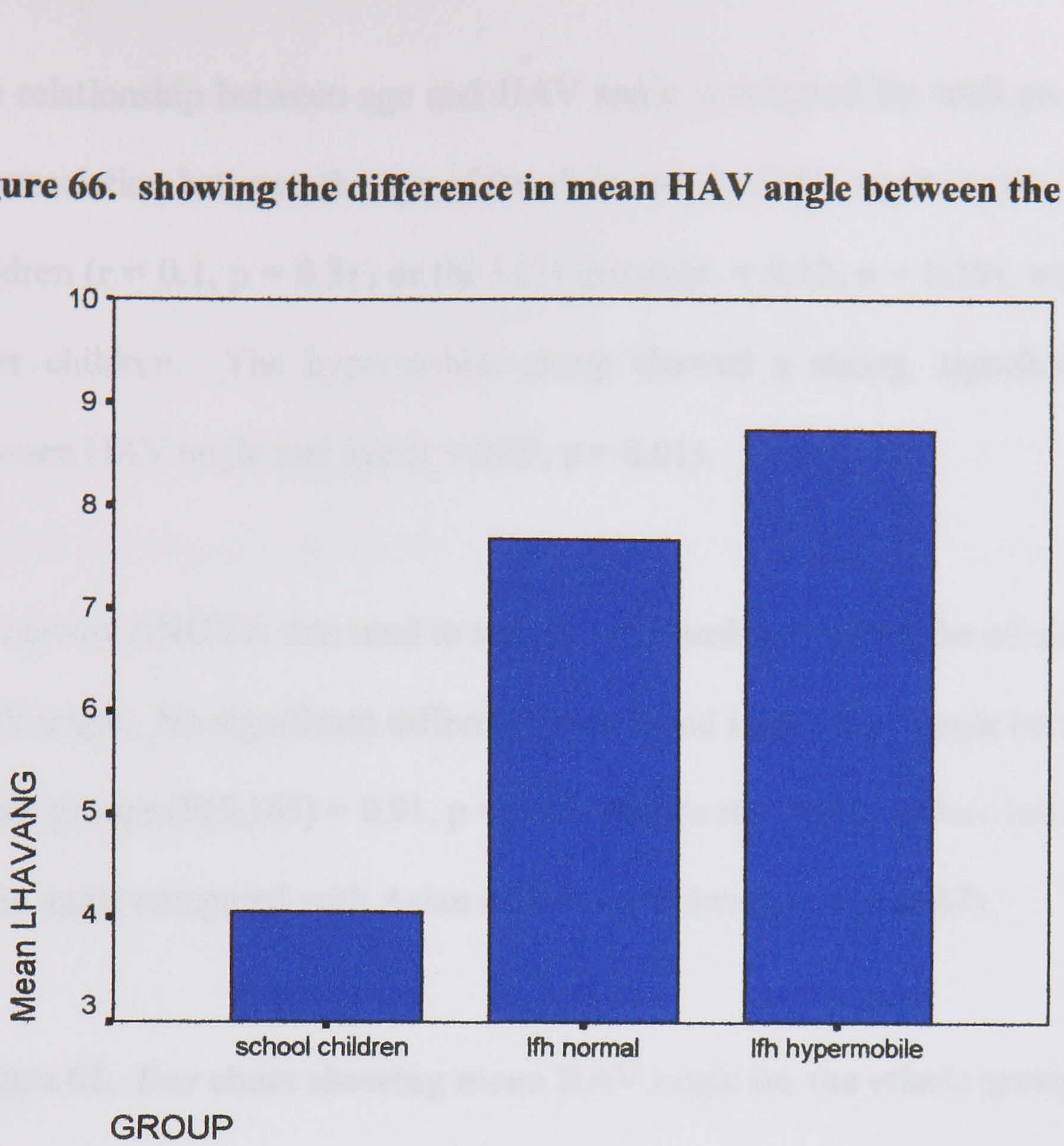
4.55 Investigation into the relationship between hypermobility and hallux abductovalgus deformity

The HAV angle was measured in a total of 99 primary school children and 71 LFH children (55 with no initial diagnosis of hypermobility, 16 with a referral of hypermobility).

The HAV angle for left and right sides were compared using a paired t-test. A statistically significant difference between sides was found ($p = 0.03$) but the difference was clinically insignificant (mean left = 5.67°, right = 5.35°) so further analysis considered the left side only.

The HAV angle in the three groups was compared (see figure 66). A difference between the groups was seen and when tested using a one-way ANOVA. A significant difference was found between the groups ($F(2,167) = 10.18$, $p < 0.001$) with the HAV angle being much greater in the two LFH groups. There was no significant difference between the LFH groups ($p = 0.54$). No child in the primary schools had HAV greater than 14 degrees but abnormal angles of HAV deformity were seen in the LFH groups.

Figure 66. showing the difference in mean HAV angle between the groups



Because of differences between the groups, the data were analysed separately. Table 26 shows the comparison between the two groups of children.

Table 26. Comparison between the primary school children and LFH patients.

	Group	N	Mean	Std. Deviation	Std. Error Mean	P value
Age	primary	97	6.92	1.87	.19	P<0.001
	LFH	72	9.96	3.35	.40	
LHAV angle	primary	97	4.00	4.10	.42	P<0.001
LHAV angle	primary	97	4.00	4.10	.42	P<0.001
	LFH	72	7.92	7.07	.84	

The relationship between age and HAV angle was tested for each group. There was no association between the age of the child and the HAV angle for the primary school children (r = 0.1, p = 0.31) or the LFH group (r = 0.12, p = 0.39), who consisted of older children. The hypermobile group showed a strong, significant association between HAV angle and age (r = 0.59, p = 0.01).

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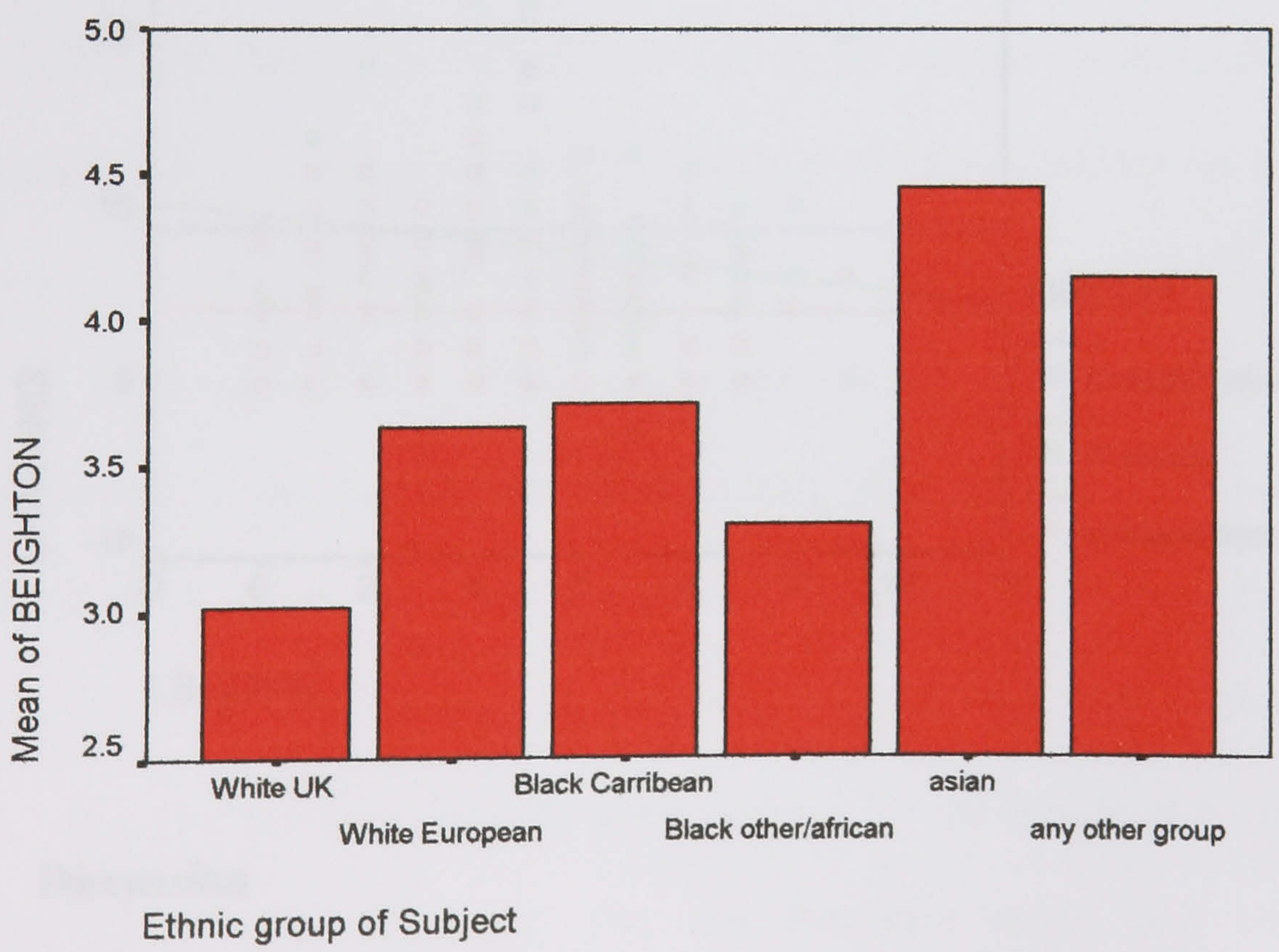
A one-way ANOVA was used to test the relationship between the ethnic group and HAV angle. No significant difference was found in the HAV angle between the ethnic groups (F(5,165) = 0.91, p = 0.48) despite the white children having a higher mean angle compared with Asian or Black children (see figure 67).

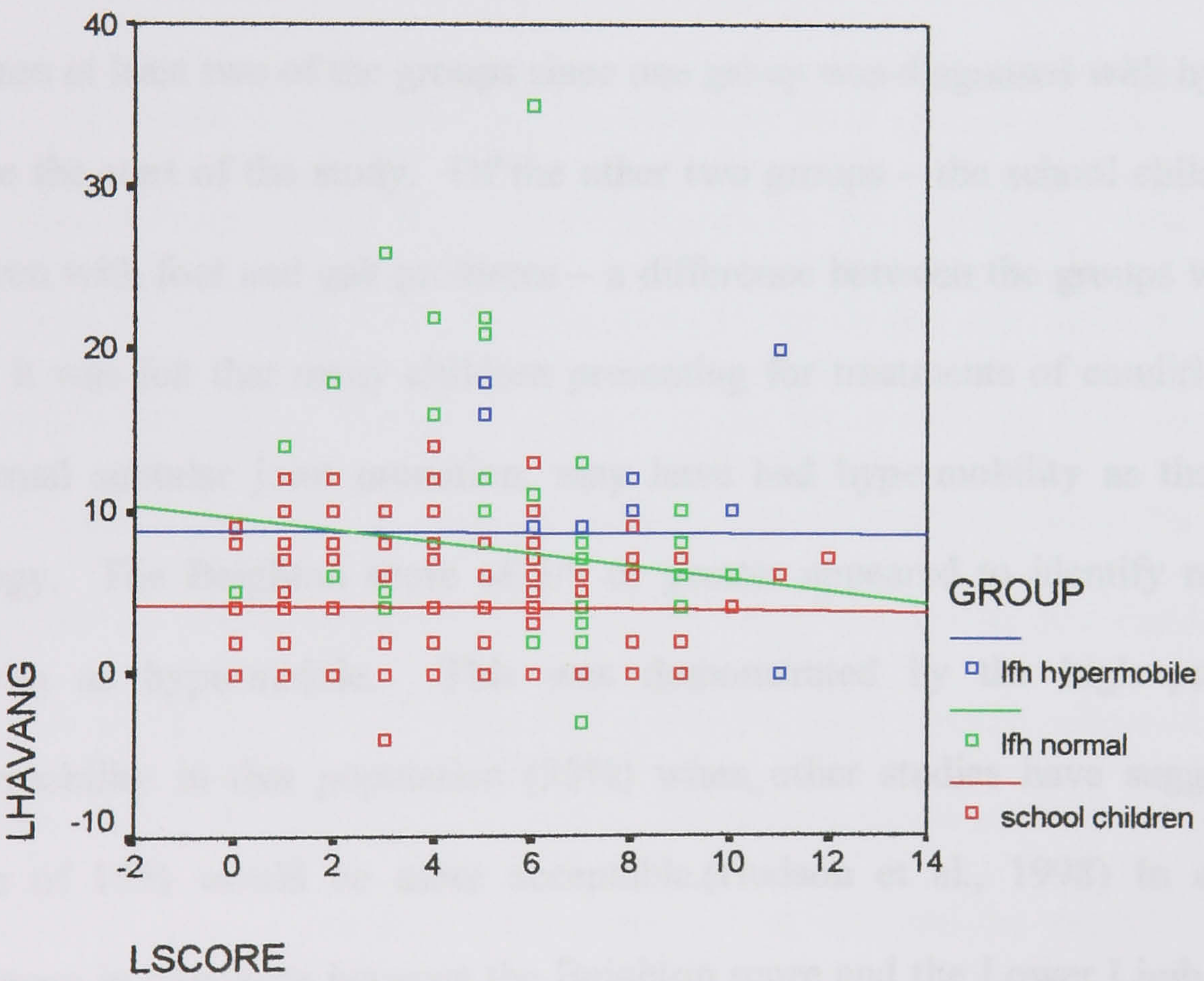
Figure 67. Bar chart showing mean HAV angle for the ethnic groups in study.



The relationship between the HAV angle and sex of the child was also tested using a one-way ANOVA. A significant association was found (F(1,166)=20.07, p < 0.001) with females demonstrating a greater HAV angle than males (female mean = 7.34°, male mean = 3.50°).

A relationship was sought between the LLAS and the HAV angle. Observation of the scatter plot shown in figure 68 did not suggest that a strong correlation existed. This was measured with Pearson correlation ($r = 0.054$, $p = 0.48$). There was no relationship between the Beighton score and the HAV angle ($r = 0.067$, $p = 0.41$)

Figure 68. Scatter plot showing the relationship between left LLAS and left HAV angle for all groups.



4.6 Discussion

Because there is no single test that can diagnose hypermobility, it is very hard to test the validity of a new assessment tool. In this study the Lower Limb Assessment Score for hypermobility was compared with the clinical opinion of two experienced paediatric podiatrists. The interobserver repeatability of the score showed that overall agreement between the two assessors was excellent despite there being some differences in the grading of individual joint movements. These differences tended to arise for the smaller joint movements where it was more difficult to judge if the criteria had been met, for example, knee rotation. However the differences tended to be smoothed out by including a large number of joint assessments in the final score. Since the two podiatrists, involved in the repeatability testing, work closely together and developed the criteria, it would be important to test the interobserver repeatability with more observers.

The study found that using a threshold of 5/9, the Beighton score did not easily discriminate between the three groups of children. A distinction was expected between at least two of the groups since one group was diagnosed with hypermobility before the start of the study. Of the other two groups – the school children and the children with foot and gait problems – a difference between the groups was expected since it was felt that many children presenting for treatments of conditions, such as abnormal subtalar joint pronation, may have had hypermobility as the underlying etiology. The Beighton score of 5/9 or greater appeared to identify many normal children as hypermobile. This was demonstrated by the high prevalence of hypermobility in that population (33%) when other studies have suggested that a figure of 15% would be more acceptable.(Hudson et al., 1998) In addition, the difference in diagnosis between the Beighton score and the Lower Limb Assessment Score, when 26.7% of the children were positive for the Beighton score but negative for the LLAS also suggested that the Beighton score was over-diagnosing hypermobility at this threshold. The high prevalence of hypermobility in the primary school children can be explained to some degree by the ethnic background of that group. The school children were predominantly Asian in background but the children attending the podiatry clinic were mainly Caucasian. Asians are known to be more flexible than other populations (Russek, 1999) and thus a cut-off score of greater than 5/9 may have been more appropriate to use to diagnose hypermobility. The difference in diagnosis between the Beighton score and the LLAS is more difficult to explain since it would be unlikely to find so many children with signs of generalised hypermobility, but no lower limb hypermobility. It is more likely that the five tests used in the Beighton score are not sensitive enough to identify hypermobility, being easy to perform by many children. By only including one joint in the lower limb (knee hyperextension), the Beighton score missed the diagnosis of hypermobility in several children (4.3%) who had lower limb hypermobility.

The LLAS appeared to discriminate between the three groups of children better than the Beighton score. In real life, flexibility is not an "all or nothing" state but there is a continuum of flexibility and it is not possible to define one point when a person becomes hypermobile. However, when studying hypermobility, it is useful to have a threshold for definition. In order to define a cut-off point to aid in the diagnosis of hypermobility, sensitivity analysis was carried out. In other studies that have used the Beighton score, the cut-off point has generally been chosen arbitrarily. Use of sensitivity analysis with the ROC curve, identified a score of 7/12 as an appropriate cut-off point. At this threshold the sensitivity was 94% and the specificity was 92.5% (1-specificity = 7.5%). This meant that only 6% of children who were hypermobile would be missed at this cut-off, whilst 7.5% of normal children would be wrongly classified as hypermobile. If the LLAS was being used in a research project and it was essential to exclude all normal children, then a score of 8/12 may be more appropriate when the specificity was found to be 99.6% (1-specificity = 0.4%), or 9/12 which would not incorrectly classify any normal children. Sensitivity and specificity can vary when populations are dramatically different and so it would be appropriate to repeat the analysis for older age groups or different ethnic groups. The positive predictive value (PPV) and negative predictive value (NPV) does differ when the prevalence of the disease differs between groups. This was demonstrated when considering the values in the three groups of children. In the group with a higher prevalence of hypermobility (LFH referred hypermobile), the PPV was also high with 83.3% of the hypermobile children in the group testing positive clinically for hypermobility. In the general population (such as the school children) where the prevalence of hypermobility is lower, the PPV was also lower with 58.3% of hypermobile children also testing positive clinically. The negative predictive values showed good results with 83.3% of the non-hypermobile children in the hypermobile group being clinically negative for hypermobility and 89.1% of the non-hypermobiles in the school children being clinically negative for hypermobility. A difficulty in the sensitivity analysis was the lack of a true gold-standard. Because the Beighton score appeared to be over-diagnosing hypermobility, it seemed inappropriate to use the Beighton score as the gold-standard. The clinical opinion of the examiners was therefore used. Initial studies suggested that the examiners were in agreement regarding the clinical diagnosis. However, the LLAS and the clinical assessment were closely associated – the assessment undertaken to gain the clinical impression was similar to the examination used to identify the lower limb assessment score.

The Beighton score did not identify the expected trend between decreasing flexibility with age in the school children, whilst the lower limb assessment score did show this trend in both the school children and the LFH group children. As expected, the true hypermobile group did not show a trend of decreasing flexibility with increasing age. In his larger study, Grahame reports a rapid fall-off of joint mobility between the ages of 5 and 11 years. Beighton *et al* suggest that the fall-off is rapid until the age of 20 years. This study was not a longitudinal study so would not be expected to show the relationship between hypermobility and age.

The cut-off point of 7/12 for the LLAS gave a more realistic values for the prevalence of hypermobility (21%) in the normal population (school children). The prevalence of hypermobility in the hypermobile group was low at 52% of the group compared with the Beighton score that found 60% of the group as hypermobile. For both these scoring systems, the prevalence of hypermobility in the hypermobile group was expected to be higher. It was unclear in the children being referred, how the diagnosis of hypermobility was made. The diagnosis may have been based on the Beighton score and thus, given the findings in the school group where the Beighton score was found to over-diagnose hypermobility, the LLAS would be lower. If this was the situation, the prevalence with the Beighton score should have been closer to 100%. The lower Beighton score may then reflect examiner bias where more strict criteria were applied when measuring the score for the study than by the doctor applying the score in a clinical situation. Alternatively, the referring practitioner may only have found hypermobility at a particular joint, for example the symptomatic joint, and given the diagnosis based upon that joint.

The analysis undertaken suggested that the LLAS might be a useful tool. The score was significantly different between the groups that were defined by a clinical diagnosis of hypermobility. It is unsurprising that a higher LLAS should agree with a diagnosis of hypermobility because the score included nearly all the joints in the lower limb and thus as more joints were found to be hypermobile, the score increased. The LLAS may therefore be a practical tool when used as a sliding scale to reflect how flexible a child is and to measure a change in flexibility over time. The score may be useful for research studies when it could be used to include or exclude certain degrees of flexibility, forming part of a trial's inclusion criteria. Providing a diagnosis for a child based upon a single cut-off point is as erroneous with this scoring system as with any of the other systems. Cut-off points should not generally be applied, the distinction between hypermobile and normal occurs gradually and not in leaps of single units as the LLAS or Beighton score measures. However, other scoring systems use cut-off points and so in this study a point was sought in order to be able to compare the LLAS to the Beighton score.

The cluster analysis showed that there were three groups of movements formed in the initial cluster. The knee draw test formed the first cluster, the second cluster included hip abduction / ankle draw / knee rotation / foot pronation and knee hyperextension. The third cluster consisted of midtarsal joint movements / subtalar joint movement / ankle dorsiflexion / 1st mtpj dorsiflexion and hip flexion. These clusters further split into what could be described as foot movements (subtalar and midtarsal joint movements) and sagittal plane movements (hip flexion / 1st mtpj dorsiflexion / ankle dorsiflexion). The lack of obvious clusters suggested that each movement was important to the scoring system.

This scoring system varied from other published scores by considering movement in different planes of motion in an attempt to differentiate the extremely hypermobile child from one who is over-flexible only at certain joints. For example, most hypermobility scores consider only the movement of extension at the knee. A child who has hypermobility at the knee in the direction of rotation (of the tibia on the femur), a positive anterior draw test as well as knee hyperextension may demonstrate a greater degree of laxity than the child who only demonstrates knee hyperextension. Alternatively, some children have excessive knee rotation and a positive anterior draw test but do not show hyperextension at the knee. The degree of hypermobility in these children would be missed in other assessment scores. Such movements may also be important in the development of long term outcomes. Hypermobility has been linked to early osteoarthritic changes. Although the pathway for this is unclear, two studies have found potential links (Sharma and Yi-Chung, 1997; Hall et al., 1995). A lack of joint proprioception has been shown in cases of anterior cruciate deficiency following trauma and hypermobility at the knee has been linked with reduced knee proprioception. In both studies, the authors considered that the effect of the reduced proprioception would lead to abnormal function and this lead to early osteoarthritic change. By failing to assess joint movements such as knee rotation or cruciate laxity, other scoring systems may be missing the diagnosis in subjects particularly at risk.

The lower limb assessment score was found not to differ between left and right sides or between males and females. Both these results would be expected since hypermobility has been shown to be symetrical and only affects females more than males in older age groups (Beighton et al., 1973; Hudson et al., 1998; Jesse et al., 1980; Fairbank et al., 1984; Mickkelson et al., 1996). Grahame reported that, in a study group aged 5-11 years, he found no difference in the degree of hypermobility between males and females (Beighton et al., 1973). Grahame's study was much larger than the present study, including 300 children, and used the Carter and Wilkinson criteria for diagnosis.

The HAV angle was found to be larger in the LFH group than the school group which was expected since some of the children had been referred for treatment of HAV or had foot problems that may be related to the development of HAV (eg. excessive subtalar joint pronation). No primary school child had HAV deformity. Kilmartin (1989) found that 2.5% of his population of 10 year old children had HAV deformity. In this group of 100 children, only 2 or 3 should therefore demonstrate the deformity, perhaps less given that the mean age of this group was younger that Kilmartin's study group. Some of the primary school children had angles up to 14 degrees and thus may have been developing the deformity but it is the lack of variation in the HAV angles that may have prevented any association between HAV and LLAS being seen.

This study did not support the findings of previous studies that have suggested that HAV is related to joint hypermobility. This study considered only a very narrow range and at such a young age it may be expected to find little variation in degrees of hypermobility compared with examining a population of age range 10 – 20 years, for example. The study also failed to show a difference in hypermobility scores between males and females. This was due to the young age group used. Associations between hypermobility and HAV deformity may become more obvious in older age groups. Further study should be undertaken to test the relationship in older age groups since it may be that HAV deformity occurs in those people who remain hypermobile but not in those that naturally reduce in flexibility over time.

The HAV angle was not associated with the ethnic group of the child. This may have been due to the narrow distribution in the HAV angles in the primary school children, who showed the most variation in ethnic group. The LFH group, who had wide distribution in HAV angle, were predominantly Caucasian. No study to date has looked at the HAV angle in children in different ethnic groups although Gould (1980) did find a difference when studying slightly older age groups.

Despite the young age group in this study, the girls showed significantly greater HAV angles than the boys. Factors other than hypermobility may therefore be involved in increasing the HAV angle that are specific to the female foot and perhaps put the female foot at risk of developing HAV deformity. Footwear was not assessed in this study and although not expected to be a factor in such young children it does need to be considered. It was noted during the study of the primary school children that the girls shoes were more influenced by fashion and wearing a shoe with a higher heel than ideal was common. In both boys and girls, the cost of shoes appeared to a factor limiting the use of good footwear in this group of children.

4.7 Conclusion

A new scoring system for measurement of hypermobility in the lower limb was introduced. The study has shown that interobserver repeatability of the scoring system was good and that in the population studied, a strong correlation existed between the clinical diagnosis of hypermobility and the lower limb assessment score. A score of 8/12 for each limb corresponded to the clinical diagnosis of hypermobility and identified the percentage of the population that was close to 2 standard deviations from the population mean. The sensitivity analysis suggested that 7/12 identified hypermobility well and it is suggested that it is around this level that the flexibility moves beyond the range seen in this group of normal, healthy children. When compared to the Beighton score, there was good agreement between the scores although the Beighton score appeared to over-diagnose hypermobility in the population and failed to recognise when a child was hypermobile in their lower limbs without having signs of upper limb hypermobility.

The study failed to identify an association between hypermobility and HAV deformity despite females being more hypermobile than males and having greater HAV angles than males. It is suggested that it is not possible to identify the influence of hypermobility in such a young group of children and it is only when joint flexibility starts to decrease and a wider range of HAV angles become apparent that the relationship between hypermobility and HAV deformity can be fully investigated.

A prospective study is indicated to follow a group of healthy children over several years, identifying which children that remain hypermobile and how this influences the HAV angles seen.

4.8 Publications and Presentations

Ferrari,J. Hypermobility: the use of a new lower limb assessment tool (abstract). Clinical and Experimental Rheumatology (2003);21:4 pp 556.

Abstract presented at the Paediatric Rheumatology European Society conference October 2003, Stresa, Italy (see Appendix V).

CHAPTER FIVE AN F-SCAN STUDY IN THE PAEDIATRIC FOOT: IS THERE A DIFFERENCE IN PRESSURE MEASUREMENTS BETWEEN MALES AND FEMALES?

Introduction

Aim

Method

Data Analysis

Results

Summary of Findings

Discussion

Conclusion

Publications and Presentations

CHAPTER FIVE

AN F-SCAN STUDY IN THE PAEDIATRIC FOOT: IS THERE A DIFFERENCE IN PRESSURE MEASUREMENTS BETWEEN MALES AND FEMALES?

5. Introduction

5.1 The history of pressure measurements

The history of pressure measurement systems have been well described, beginning with the earliest attempts to assess pressure patterns from footprints undertaken by Beely in 1882 (Stott et al., 1973; Betts et al., 1991; Alexander et al., 1990). Beely created footprints by walking over a bag of Plaster of Paris. The indent in the plaster showed the shape of the foot with the depth of the imprint being related to the pressure borne by the foot. Given that the plaster was a solid-liquid, the foot caused deformation of the plaster until pressure was equal across the foot so that areas of high and low pressures were not differentially manifest. In 1930, Morton devised a rubber mat that had triangular corrugations on the surface (Stott et al., 1973). The mat was inked and a layer of paper placed on top. As the subject bore weight on the paper, the ink left an impression of the corrugations. This method was developed by Harris and Beath and is still used today. Harris and Beath added thin ridges of differing heights to the mat so that as more pressure was added, the deeper ridges came into contact with the paper and the resultant footprint showed varying densities of ink related to the different pressure points under the foot (Lord, 1981). Calibration of the mat was attempted (Silvino et al., 1980) but the pressure recordings were

reported to have poor sensitivity (Hughes et al., 1987). A disadvantage of this system was the inability to record a time axis in relation to the pressure measurements.
In 1934, Elfman developed the first pressure system using light reflection and dynamic measurements. When standing on a plate of glass lit by angled light, the pressure areas were highlighted and when each stage of walking was photographed, the changes of pressure during gait were shown. Such a method was developed into the Pedobaragraph in 1960. The Pedobaragraph consisted of a thick plate of glass with force transducers at each corner and a mirror angled at 45 degrees. Pressure on the glass was transferred to a plastic foil, which in turn changed the internal reflection of light created by fluorescent tubes. The amount of light escaping was recorded and converted by a computer into a visual image (Corbett et al., 1993). The amount of light escaping was proportional to the pressure applied and so the system could be calibrated and was found to be sensitive to pressure changes (Hughes et al., 1990).

The application of electrical methods to measure force began in 1953 when Holden and Muncey used a capacitance pressure transducer, in a specially constructed shoe, to measure the loads under the heel (Stott et al., 1973). This was developed later by attaching transducers directly to the soles of the feet. The in-shoe construction allowed for multiple footsteps to be measured whereas the previous force plates could only measure one step. With transducers so close to the foot it was found that normal gait was not achieved since the subject was aware of the transducer and altered weightbearing accordingly. Stott *et al* (1973) introduced a force plate made of 12 beams with 8 strain gauges on each beam that would measure longitudinal tension. The plate provided a dynamic reading of force against time but was too small to measure the whole foot.

In the majority of cases, the development of pressure measurement devices concentrated on the measurement of vertical forces. The measurement of horizontal forces – shear forces – received very little attention (Lord, 1981). In 1983, Pollard *et al* developed a shear transducer. Displacement of a semi-conductor in a magnet field produced a change in resistance which was proportional to the force applied. Today very few systems measure horizontal forces despite the association between both callous formation in healthy individuals and ulcer formation in people with diabetes (Walker and Hui-Ji Fan, 1998).

The development of computerised functional gait analysis systems has been considered one of the greatest advances in podiatry over the last 20-30 years (Young, 1993). In this time, the limits of a single force plate have been recognised and in-shoe measurement devices have been developed. The force plate can only measure one step and multiple plates are required to produce a series of steps. Unless flush to the weightbearing surface, the subject tends to adapt the gait to step onto the force plate or change their stride pattern to time the loading of the plate. A truly natural gait is rarely achieved. Compared to the in-shoe devices, the force plate is quick to use, allows free walking as no wires are attached and is user-friendly for children. In comparison, a system that measures the foot pressures inside the shoe, if slim enough, does not cause the subject to adapt the gait. An in-shoe system will allow for direct comparison to be made with varying in-shoe environments – for example the effect of an orthosis (insole) on foot pressures. Time is required to shape and fit the insoles. The insoles have a limited life span and when in use, many wires are strapped to the patient which may influence gait and may not be safe to use with children. Multiple footsteps can be measured.

Several systems have come onto the market in recent years and have been reviewed by Hurkmans *et al* (2003). The main systems include the F-Scan and EMED systems. F-Scan uses electrical resistance to measure pressure. The system uses material properties that change their resistance under pressure. EMED uses the principles of capacitance. Pressure changes the distance of two wires across a cell and therefore the capacitance of the sensor changes.

Both systems have a force platform or an insole for use. With any system, the number and size of the transducers is important. Betts reports that the pressure on a foot can vary over less than a distance of one centimetre: therefore a transducer that is 1cm square will average the amount of pressure recorded and may not define high-pressure areas with sufficient precision (Betts et al., 1991).

5.11 The F-Scan system

The F-Scan system has been subjected to scrutiny regarding its reliability (Zong-Ping Luo et al., 1998). The insole system has been found to have a uniform response to the loading of all the cells in the matrix. The loading response in all cells was linear, however the output was highly dependent on the surface contact hardness so that as the hardness of the surface increased, the output increased. The insole therefore requires a standardisation in use between subjects – for example, in the type of shoe worn with the insole. The output has been found to increase as temperature increase above 30°C, so care needs to be taken in controlling the in-shoe environment. The system is sensitive to the loading speeds of the foot onto the insole and so calibration of the system needs to be undertaken in a fashion similar to the test conditions. Ahroni *et al* (1998) found that the pressure measurements varied within subjects for repeated tests over 4 steps on two occasions. They found that the variability in readings was greatest under the hallux and least under the metatarsal heads. This variability was represented by coefficients of variation ranging from 0.116 to 0.217. The intraclass correlations for testing the results on two occasions gave values between 0.493 and 0.832, which was reported to be fair to good. The authors were not able to determine whether the variations were due to the system (ie. in-shoe environment changing) or whether they were due to variations within the patient. These results were slightly lower than those found by Cornwall and McPoil (1997) using the EMED system when ICCs ranged from 0.625 for the hallux to 0.974 for the metatarsal heads. Cornwall and McPoil controlled for cadence (steps per minute).

The insoles used for the in-shoe recordings have a limited life span, becoming unreliable with over-use. The life span is limited to around 30 strides and this increases the costs of maintaining the system. In a report of the system, Nicolopoulos *et al* (2000) cited several other trials where the insole system was felt to be unreliable, with errors occurring at pressures of greater than 200kPa. The insoles did appear to correlate well with the forces measured by other force platforms but overall, serious concerns were raised regarding the reliability of the system. This was in contrast to a repeatability trial by Randolph *et al* that found the insole system gave similar results when tested across 10 subjects walking 3 times (Randolph et al., 2000). Rose *et* al undertook several repeatability studies that included looking at the variability in pressure measurements over separate days and when the insole was repeatedly taken in and out of the shoes. Although the analysis of the data was poorly presented, the results suggested that the variability under different conditions was large (Rose et al., 1992).

The same type of repeatability studies appear not to have been applied to the force platform although the platform has shown good correlation of results when compared to the insole (r=0.93) and has been used to calibrate the insole (Mueller and Strube, 1996).

5.12 Normal foot pressures in adults

The area of maximum pressure under the foot varies during walking, with foot type, walking speed, age and with gender (Walker and Hui-Ji Fan, 1998; Soames, 1985; Stott et al., 1973; Hutton and Dhanendran, 1990; Hughes et al., 1991). The cadence has been found to have the greatest impact on peak pressures such that peak pressures increase as cadence increases. An increase of up to 60% was noted in the 1st and 2nd metatarsals as the number of steps per minute increased (Zhu et al., 1995). Any dynamic study on walking pressures should therefore control for cadence.

Bennett and Luplock (1993) used the Musgrave force platform to measured the forces in the feet of 86 volunteers, walking at a fixed speed. The three most consistent footprints from six attempts were chosen for data analysis. Using the average maximum pressure during the stance phase, the central 3 metatarsals were found to take the greatest pressure with the hallux, 1st metatarsal head and 5th metatarsal head taking decreasing force, in that sequence. The hallux was seen to take more pressure in females compared with males, otherwise females showed reduced pressure at all other areas compared to males but with the same pattern of distribution. The difference between males and females was not tested for statistical significance but the graphical representation suggested that the difference was small. Walker and Fan

(1998) found that the central metatarsals showed the greatest pressure regardless of foot type but the distribution of pressure across the forefoot varied significantly with foot type. This was in agreement with Hughes *et al* (1987) who compared three different methods of measuring foot pressure in 10 subjects. With all techniques, the second metatarsal head showed the greatest pressure with the 3rd or 1st metatarsal head taking the next greatest pressure. The study was repeated with 100 subjects and new equipment (Hughes et al., 1993) and again showed the maximum pressures occur over the central metatarsal heads. Holmes *et al* (1991) also found the same distribution of pressure measurements in a study of 20 adults. The females had greater pressure under the hallux than males but there was no significant difference in the pressure distributions between males and females.

Hutton and Dhanendran (1990) found that the hallux carried twice the load of the lesser toes and found that the first metatarsal carried more load than any other metatarsal but, given that it had a greater size, the pressure was less than for the second metatarsal. Hayafune *et al* (1999) pointed out that the force under any area of the foot would vary during the stance phase, depending upon whether the heel was weightbearing, and the position of the body over the foot. In the study of 42 subjects using the EMED force plate system, it was found that the peak pressures (as a percentage of body weight) occurred under the hallux and 2nd metatarsal head during the terminal stance peak phase, with the 1st metatarsal head recording the next greatest pressure. Together, the hallux and 1st metatarsal took 42% of the total peak load. The authors pointed out the difficulties of comparing measurements due to the differing size areas on each foot making pressure measurements difficult but more relevant than force measurements. The authors found a negative correlation in the pressures between the 1st and lateral metatarsals such that if the pressure increased medially, it decreased laterally. No correlation was found between the pressure under the 1st and 2nd metatarsals and the 1st metatarsal and hallux.

In a study of 160 subjects aged 5-78 years old, Hughes *et al* (1990) found that the hallux showed the greater pressure followed by the 2nd and 3rd metatarsals and then the 1st metatarsal. A positive correlation was shown between peak pressure and subject weight.

When the mean standing pressure under the foot was compared in children, adolescents and adults, Betts *et al* (1991) reported that the pressures were very similar with only a small increase seen in the adults. Despite the increase in foot size into adulthood, the authors felt that the spread of the load around the foot kept the peak pressures within narrow limits.

Few studies have looked at the timing of peak pressures in the foot. Betts *et al* (1991) demonstrated that the 2nd metatarsal pressure peaks after the first metatarsal, in their study of 17-56 year olds, using the pedobaragraph.

5.13 Normal foot pressures in children

Few studies have considered the pressure distribution under the feet of children.

Children do not develop a mature gait pattern until they are around 7 years old and so a pressure distribution similar to an adult would not seen be expected until then and changes with age may occur (Sutherland et al., 1980). In 1980, Aharonson *et al* (1980) undertook a study on 46 children aged 4-6 years old using a pressure mat with an optical sensitive elastic material positioned between two glass sheets. When the foot was divided into anterior, middle and posterior regions, 35% of the pressure was found to be placed on the forefoot. The author discussed problems with using children in a study such as their poor balance leading to instability on the pressure mat, influencing the readings taken.

A study on 15 young children aged between 14 and 32 months of age was undertaken in 1991 (Hennig and Rosenbaum, 1991). Using the EMED force platform, the children crossed the platform at a self-selected speed and the average of 3 recordings was taken. As with many of the other trials on adults, any footprint that was considered abnormal was eliminated from the study. This was a serious concern for these studies since it is often unclear on what grounds the footprints were considered abnormal and removing them from a study because they looked incorrect would influence the results. When compared with adult pressure measurements, the children showed lower peak pressures. The pressure distributions were similar with the hallux bearing the greatest pressure followed by the central metatarsals, 1st metatarsal and finally the 5th metatarsal. The "relative impulse" under each area was calculated by finding the force on the area of the foot during contact and dividing it by the sum of all the forces. Expressed as a percentage, this would show the forces independent of body weight and foot dimensions. When compared to adults, the children showed significantly less central metatarsal loading, despite the pressure distribution remaining similar. The arch area took increased force compared with adults, which would be expected since the developing foot tends to have a low arch when weightbearing. There was a significant negative correlation between age and force under the arch which the author interpreted as the longitudinal arch developing over time and thus taking less weight with age and the central metatarsals taking increased weight.

When running, both children and adults showed significantly greater force under the hallux and less force under the central metatarsals. Forces under the foot are known to increase with speed or footfall. Children under 5 years old have a much greater cadence than that of an adult but Hennig (1991) found that speed of walking did not affect the results until the child was running.

The study was repeated in 1994 with 125 school children aged 6-10 years (Hennig et al., 1994). Five trials for each child were collected with apparently abnormal footprints being repeated rather than discarded. Again, the distribution of forces showed a similar pattern to the adults with the hallux showing greatest mean peak pressures, followed by the central metatarsals then the 1st metatarsal area. There were no differences in the forces under the arch area between the children and adults. When compared to the younger children, the 1st metatarsal in older children and adults took significantly increased force. This was related to the increased 1st ray stability with reduced 1st ray hypermobility that was believed to occur with the lessening of subtalar joint pronation in the older child. Despite the differences in the 1st metatarsal head forces, the forces under the hallux remained identical. Positive correlations were seen in children for all areas of the foot for relative body weight and peak pressure with exception of the midfoot area. The study found no differences in the size or distribution of the peak pressures between boys or girls, despite differences in growth of each gender between the ages of 6-10 years.

D'Amico (1998) described the use of the FScan in-shoe systems to measure the pressures in the paediatric subject. A method of measuring the degree of pronation or supination of the foot was given that used the position of the centre of force in the foot. The distance from the medial border of the foot to the centre of force trajectory was divided by the distance from the lateral border to the trajectory. Values less than 1 indicated that the centre of force was on the medial side of the foot and thus the foot was pronated. The author identified the difficulties in using the F-Scan insole system in children, with their ability to follow instructions and their short attention span being particular problems. Cornwall and McPoil (2003) point out that the validity of the use of centre of pressure (COP) indices as a method of identifying pronation and supination is unproven. The authors questioned the validity of the centre of pressure measurements such as the index created by dividing the area medial to the COP by the area lateral to the COP or by dividing the relative forces. The authors found that such indices did not correlate with the rearfoot position and thus would not indicate whether the foot was pronated or supinated. The authors attempted to measure the triplanar movements involved in pronation and supination and correlate the rearfoot position with the COP index. No correlation was found. The authors did admit that their method may have been too simplistic to determine a correlation since the COP would be related to overall body movement consisting of trunk and lower limb mechanics rather that to simply rearfoot movements. They suggested that COP measurements should be used to indicate where the pressure is being placed rather than to describe the biomechanical position of the foot.

5.14 Pressure measurement in HAV deformity

Differences in pressure measurements in subjects with hallux valgus deformity and subjects without HAV deformity have been undertaken by several authors (Blomgren et al., 1991; Hutton and Dhanendran, 1990; Hughes et al., 1990; Kernozek et al., 2003; Betts et al., 1991). The results of these studies have been conflicting. It has been found that the pressure under the 1st and 2nd metatarsals decreases when HAV deformity is present. For example, Blomgren *et al* (1991) found, in their study of 66 subjects with HAV and 60 control subjects using the EMED system, that the pressure on the hallux was the same in both groups but was significantly less on all the metatarsals (except the 5th) in the HAV group (p>0.001). The HAV group showed greater pressure in the tarsal area but had significantly less pressure on the heel region. Blomgren *et al* used three recordings of maximum pressure, with the first two attempts being practice runs and the third recording being used for analysis. Cornwall and McPoil (1997) found that the reliability of the EMED system was only acceptable when the mean of 5 recordings were used which throws doubt on the accuracy of this study. Kernozek *et al* (2003) used the mean of 5 acceptable recordings in their study using the EMED platform and found no significant difference in peak pressure under the medial forefoot between the control group (n=51) and the HAV group (n=40). There was a significant difference for peak force with the HAV group showing less force under the medial forefoot. Of note, the HAV group had a lower mean body weight than the control group. Under the hallux, the peak pressure was significantly greater in the HAV group but the peak force was significantly less than in the control group.

Hutton and Dhanendran (1990) compared peak force in feet with and without HAV deformity. Using a force plate with 128 load cells, 74 normal subjects aged 6-65 years old were compared to 34 females with HAV deformity using the mean of three recordings. In agreement with Kernozek *et al*, in HAV deformity, the 1st and 2nd metatarsals carried less weight than the control group with the weight being carried laterally on the 3rd-5th metatarsals.

Hughes *et al* (1990) showed weak, non-significant associations between HA angles and peak pressure measurements under the hallux in their group of 160 subjects (R^2=0.05). In general, the central metatarsals showed greater loading with increased HAV deformity.

Betts *et al* reported great variability in the peak pressure under the hallux in HAV subjects but reported a significant number of feet had reduced or absent pressure measurements whilst 33% of the HAV subjects had pressure measurements within normal limits.

In a study of 64 patients with hallux valgus deformity aged 15-65 years old, Stokes *et al* (1979) considered the centre of pressure in the foot. The centroid was expressed as the distance from the medial border of the forefoot to the centre of pressure, divided by the total width of the forefoot. It was found that the position of the centre of pressure (COP) was generally medially placed but did not vary with age, weight, height, sex or walking speed of the subject. Subjects with HAV deformity had a decreased loading of their toes.

The change in load bearing may occur due to HAV deformity or may cause HAV deformity. No long-term study has been undertaken to consider whether the change seen with HAV deformity precedes the condition. Changes in weightbearing patterns may occur due to poor foot function or as a pain avoidance mechanism. In a study using the EMED system on 100 patients with hallux valgus deformity, the peak pressures under the forefoot were significantly greater in subjects with forefoot pain and the weight shift from the hallux to the lateral forefoot was also greater when forefoot pain was present (Waldecker, 2002). Kernozek *et al* found that forefoot pain was a strong predictor of subjects in the HAV group. This was unsurprising given that no patient in the control group had forefoot pain. The authors did not look at the association between pain and pressure patterns.

No study has considered pressure measurements in juvenile HAV deformity.

Table 27 summarises the pressure finding of the studies described. Overall, the most frequently seen pattern of loading in normal feet appears to show the hallux taking greatest pressure and the 5th metatarsal taking the least:

hallux > central metatarsals >1st metatarsal > 5th metatarsal.

Table 27. Pressure measurements

	Walking Peak Pressures			
Study Equipment Population	1^{st} met	Central mets	5^{th} met	hallux
Hennig 1991 EMED 15 children (14-32m)	95kPa	99kPa	87kPa	**141kPa**
Hennig 1991 EMED 111 Adults	312kPa	380kPa	215kPa	**416kPa**
Hennig 1994 EMED 125 children 6-10yrs old	158kPa	206kPa	109kPa	**245kPa**
Kernozek *et al* 2003 EMED 51 adults, 44.2 yrs old	39.4kPa	-	-	**43.2kPa**
Hayafune *et al* 1999 EMED 42 adults, 20-59 yrs old	372kPa	435kPa	128kPa	**462kPa**
Blomgren 1991 EMED 60 Adults	**37N/cm**	27N/cm	31N/cm	30N/cm
Bennett and Duplock 1993 Musgrave 74 adults, 18-30yrs old	3.1kg/cm²	**4.2kg/cm²**	2.3kg/cm²	3.5kg/cm²
Holmes *et al* 1991 Pedobaragraph 20 adults	2.6kg/cm²	**4.2kg/cm²**	2.4kg/cm²	**4.2kg/cm²**
Waldecker 2002 EMED 50 HAV Adults	34.4N/cm²	29.09N/cm²	**56.35N/cm²**	
Waldecker 2002 EMED 50 HAV Adults with pain	**41.12 N/cm²**	19.12N/cm²	39.08N/cm²	
Blomgren 1991 EMED 60 Adults with HAV	**40N/cm**	21N/cm	25N/cm	26N/cm
Kernozek *et al* 2003 EMED 40 adults with HAV, 46.9 yrs old	43.3KPa	-	-	**53.9KPa**

There are difficulties in comparing measurements between studies. Different equipment has been used under different situations. Also few studies have included a rigorous method of dividing the foot into separate regions. Cavenagh *et al* (1987) described such a method whereby the foot was divided into 10 regions. The authors noted that this method was open to error as each individual has anatomical differences that would influence how the regions are created but does not state whether any repeatability or reliability tests were applied. Hutton and Dhanendren (1990) used the lateral border of the hallux extended proximally to define the position of the 1st metatarsal head.

Several studies mention the variability in pressure measurements between repeated footsteps (Hayafune et al., 1999; Hughes et al., 1993; Holmes et al., 1991; Cornwall and McPoil, 1997; Akhlaghi et al., 1994) Holmes *et al* (1991) considered the repeatability of scans taken on the Pedobarograph. They found that the between trial variance was greater than the between day variance and accounted for 5-10 % of the variation in results seen. The heel showed least variability with the medial and lateral borders of the foot showing greatest variability in measurements. The authors recommended that at least three recordings were made on one day of measurement for any study. The coefficient of variation was used to express the variability (SD/mean x 100%) in footprints. Cornwall and McPoil (1997) found that the reliability of the centre of pressure measurements for between trial footprints was within acceptable limits (ICC >0.75) when at least five repeated trials were used in the EMED system. Hughes *et al* confirmed this, finding that the mean of three repeated walks gave a coefficient of reliability of 0.904 compared with 0.759 for a single walk on the EMED force platform, in the study of 10 volunteers, controlled for walking speed.

In a study using transducers made of piezoelectric film, Akhlaghi *et al* (1994) found individual variations in peak pressure under the 1st metatarsal head of between 66 and 100% for 10 consecutive steps for 17 subjects. The authors also suggest that several sequential footsteps should be measured, excluding the end steps where deceleration influences the pressures. This study did not control for footwear so the influence of the soling material of the shoe on the variations was not evaluated and cadence was not controlled for during the individuals' walk. Peters *et al* (2002) investigated the differences between loading the EMED force plate on the first step of gait and loading the plate on the third step of gait. They found that there were no significant differences in pressure measurements between methods of loading the force plate. The total contact times did show significant differences between techniques, being longer for the "first step" technique. They found that the "first step" technique was more repeatable (ICC = 0.40 to 0.59) than the three step approach (ICC = 0.31 to 0.39) and concluded that the one-step technique "*could gather initial information on areas of high peak pressure, thus providing a screening tool that requires minimal resources*". The study was small, including only 10 subjects and the parametric tests applied may not have been appropriate for the small numbers involved.

5.15 Juvenile Hallux abductovalgus

Juvenile HAV deformity is believed to have different etiological factors to the adult deformity. Coughlin and Mann (1987) reported differences between juvenile and adult HAV deformity when describing the pathological features associated with the deformity. They reported that the bony overgrowth of the joint and bursa formation were rarely seen in the juvenile condition. They failed to comment that such pathological features in the adult probably occur after many years and continually wearing poor footwear. The juvenile deformity is usually better looked after in terms of footwear until the child is old enough to make their own footwear choices. No study reporting the long-term pathological changes in JHAV has been published.

Kilmartin and Wallace (1992) undertook a large study in the early 1990s which identified factors associated with juvenile HAV deformity and furthered the opinion that they were differences compared to the adult condition. Kilmartin found that excessive subtalar joint pronation, frequently reported to be associated with the adolescent and adult condition (Kalen and Brecher, 1988; Tanaka et al., 1999; Root et al., 1977a; Greenburg, 1979) was not a factor associated with the juvenile deformity. Further study identified a plantarflexed 1st ray position as being significantly related along with hypermobility in the forefoot (Kilmartin et al., 1991). The mechanical position of the 1st ray (in plantarflexion) would theoretically lead to it bearing weight early in the stance phase of gait. The hypermobility in the forefoot would allow the 1st metatarsal to be displaced upwards by the ground reaction force. In the adult pronated foot type, the pronation is believed to cause the 1st metatarsal to bear weight early and to be forced into a dorsiflexed position (Root et al., 1977b). Due to the axis of motion of the 1st ray, dorsiflexion of the ray is usually accompanied by adduction and the increased intermetatarsal angle (metatarsus primus varus deformity) initiates the secondary soft tissue changes that progresses the severity of the condition.

As reported in chapter 1, juvenile HAV deformity predominantly affects girls. Although Kilmartin identified associated factors with the juvenile deformity, it was unclear if they predominated in females as well. Only a small number of the HAV group were boys (n=13) therefore it would be difficult to look at the factors associated with HAV deformity in males and females. Although Kilmartin identified forefoot hypermobility as being an associated factor with JHAV deformity, generalised or lower limb hypermobility was not reported on. As reported in chapter 4, increased flexibility is a predominately female condition and has been found to be associated with HAV deformity in adults. In younger children (5-11 year olds) an association with HAV deformity was not found possibly due to the low prevalence of HAV deformity in the study group. To be a cause of HAV deformity, hypermobility may affect the foot in several ways. It may be that when an external force is applied to the 1st ray complex, no constraining force is present due to hypermobility of the ligaments and deformation of the 1st metatarsophalangeal joint occurs easily. It is also possible that the over-flexible limb functions in a different way to the normal limb. For example, increased subtalar joint pronation has been reported with generalised hypermobility (Al-Rawi and Nessan, 1997) and joint proprioception is reduced (Hall et al., 1995). The abnormal functioning of the lower limb may place abnormal forces on the 1st ray complex and thus lead to HAV deformity. Differences in gait will cause a difference in the distribution in forces under the foot and these may be identified from pressure measurement. The correlation between pressure measurements and hypermobility has not previously been reported.

In summary, it can be seen that the distribution of pressure under the foot has been investigated in both children and adults. However the data available for children is limited with no information regarding the pressure distribution in children with HAV deformity or when hypermobility of the joints is present. There are minimal data on comparison of pressure measurements between males and females.

5.2 Aim

This study aimed to test whether a functional difference in males and female feet could be identified through the investigation of foot pressure measurements. The influence of increasing joint flexibility on the pressure distribution under the foot was considered and the association between HA angle, 1st ray position and pressure measurements were also assessed.

5.3 Method

Ethical approval was granted from Camden & Islington NHS Trust Ethical Committee (see Appendix VI). A convenience sample of children attending the London Foot Hospital over a 6 month period were invited to participate in the study when they satisfied the exclusion criteria (see table 28). The sample included children were referred to the unit by their GP or consultant for the treatment of foot or gait problems.

Table 28. Exclusion criteria for study group

- Presence of neurological, orthopaedic or connective tissue disorder preventing normal gait, normal joint movement or affecting balance
- Previous surgery to the foot
- Inability to follow instructions for loading the pressure mat
- Aged less than 5 yrs or greater than 16 yrs old
- Non consent

Because the reliability of the F-Scan insole was unclear and because the study involved young children, the F-Scan force platform (Texscan® Boston, MA) was chosen for use.

The F-Scan mat has 2228 individual pressure sensing cells (the in-shoe sensor has only 960 cells) with a spatial resolution of 1.4 sensors/cm^2. The mat is 436mm x 369mm in size giving a large enough area for the whole foot to be placed on the sensor area. The sensors are sampled at a rate of 40Hz.

Recording session

Calibration on the pressure mat was undertaken using the manufactures instructions. The subject was weighted using calibrated scales. The subject then stood on the F-Scan mat with both feet before being asked to stand on one foot. If balance was difficult, the child was supported lightly by their parent holding one hand. The F-Scan software calibrated the footprint using the known weight of the child.

It was considered that the younger children would not be able to walk to a set cadence or be able to judge loading of the mat from a distance. Therefore, in order to reduce the impact of these factors, a “first step” measurement technique was used (Peters et al., 2002). The subject was asked to stand behind the mat. With their first step they stepped onto the mat with one foot, whilst the other foot stepped over the mat for the second step. The child was asked to walk around the mat and stop behind the mat, regaining their balance before taking their next step onto the mat again with the same foot. This was continued with 3 or 5 footprints being collected within the 4000 frame scanning time. The process was repeated for the opposite foot. Several practice attempts were made to familiarise the child with the technique and normalise the footstep prior to the recording of each foot.

A joint examination was carried out to determine the level of flexibility of the joints. This was undertaken using the lower limb assessment score (LLAS) (see chapter 4) and using the Beighton score for generalised hypermobility.

The 1st ray position was measured using the Kilmartin Sagittal Ranger with the child prone. This device has been shown to be repeatable. It has a platform to rest the 2nd to 5th metatarsal heads upon, whilst the platform under the 1st metatarsal head can move up and down independently alongside a ruler to identify dorsal and plantar movement measured in millimetres (Kilmartin, 1988). The HA angle was measured using a finger goniometer with the child weightbearing (Kilmartin, 1988).

Footprint analysis

The peak pressure on each footprint was measured at 4 locations. These were the heel, the hallux, the 1st metatarsal head and the 2nd-5th metatarsal head area. The foot was divided for analysis using a similar method to Hutton and Dhanendran (1990). On each footprint, a box was added which was the size of the area being considered. The hallux was measured first with a box being added that corresponded to the proximal and lateral edge of the digit. The box for the first metatarsal ran from the proximal edge of the box for the hallux and was continuous on the lateral side with the lateral edge of the box for the hallux. The box for the lesser metatarsals ran from the lateral edge of the box for the 1st metatarsal across to the 5 metatarsal, lateral border enclosing the forefoot. The box for the heel enclosed the weightbearing surface of the heel. The four areas are shown in figure 69. The software highlighted the mean peak pressure area in each box created over a 4-sensor cell area (shown as black boxes in figure 69).

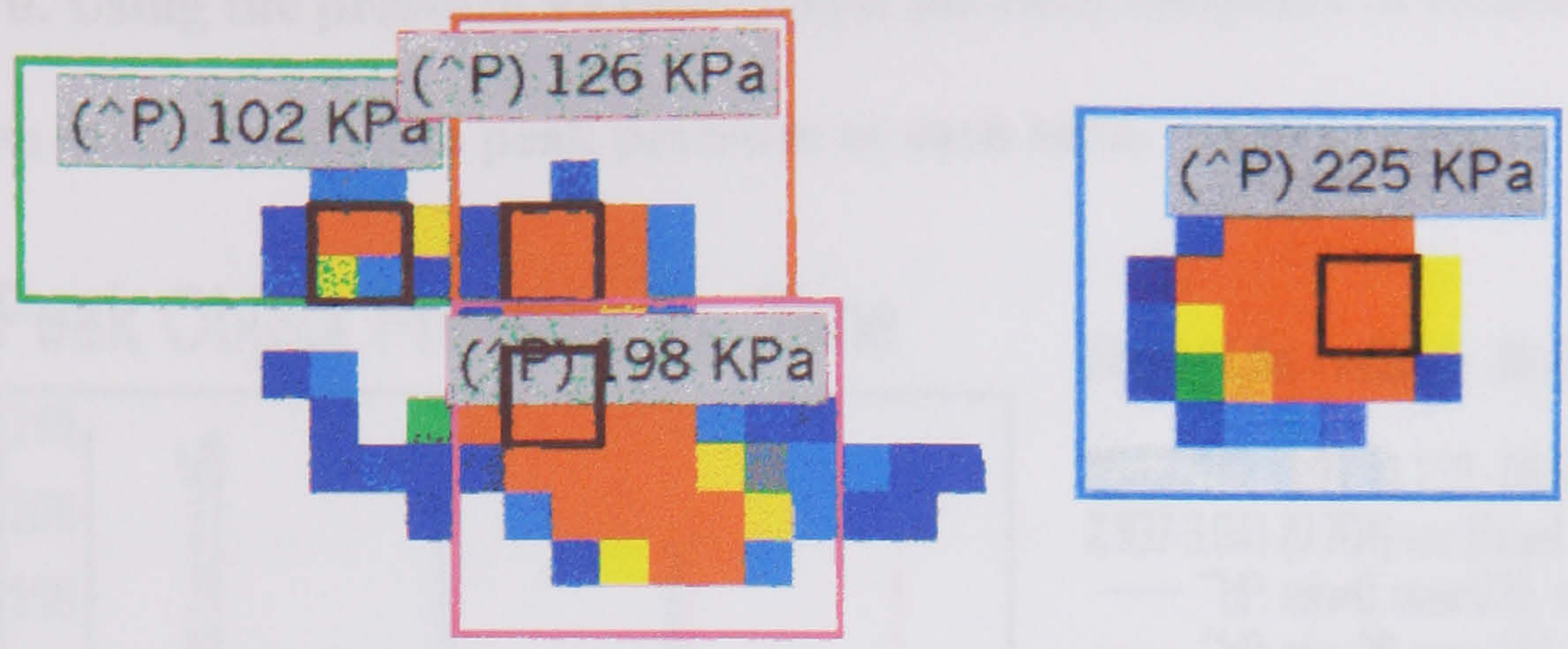
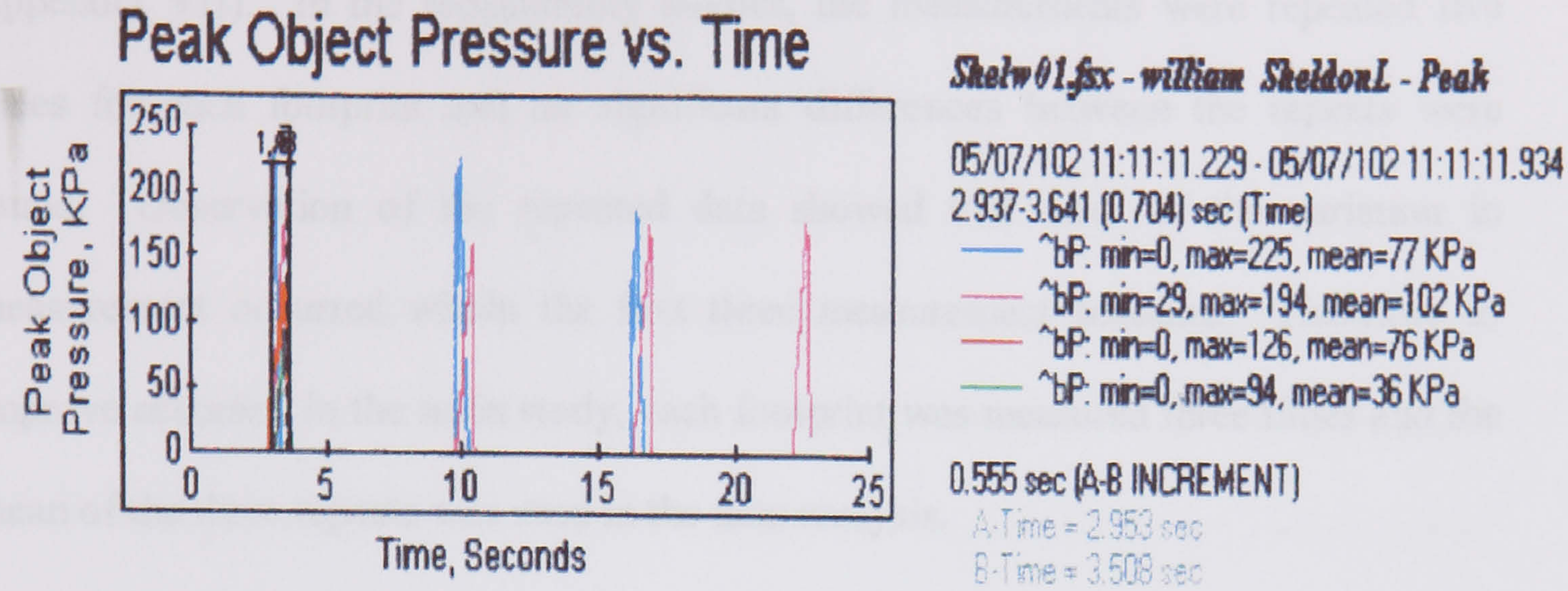


Figure 69. Method of applying boxes to identify regions of interest.

The time from initial contact until the peak pressure at each area was measured from the pressure versus time graph generated by the software (see figure 70). The software allowed vertical lines to be moved across the graph and aligned with the start of contact and the peak pressure phases. The time between initial contact and loading of the 1st metatarsal head and initial contact and loading of the 2-5th metatarsal areas was measured.

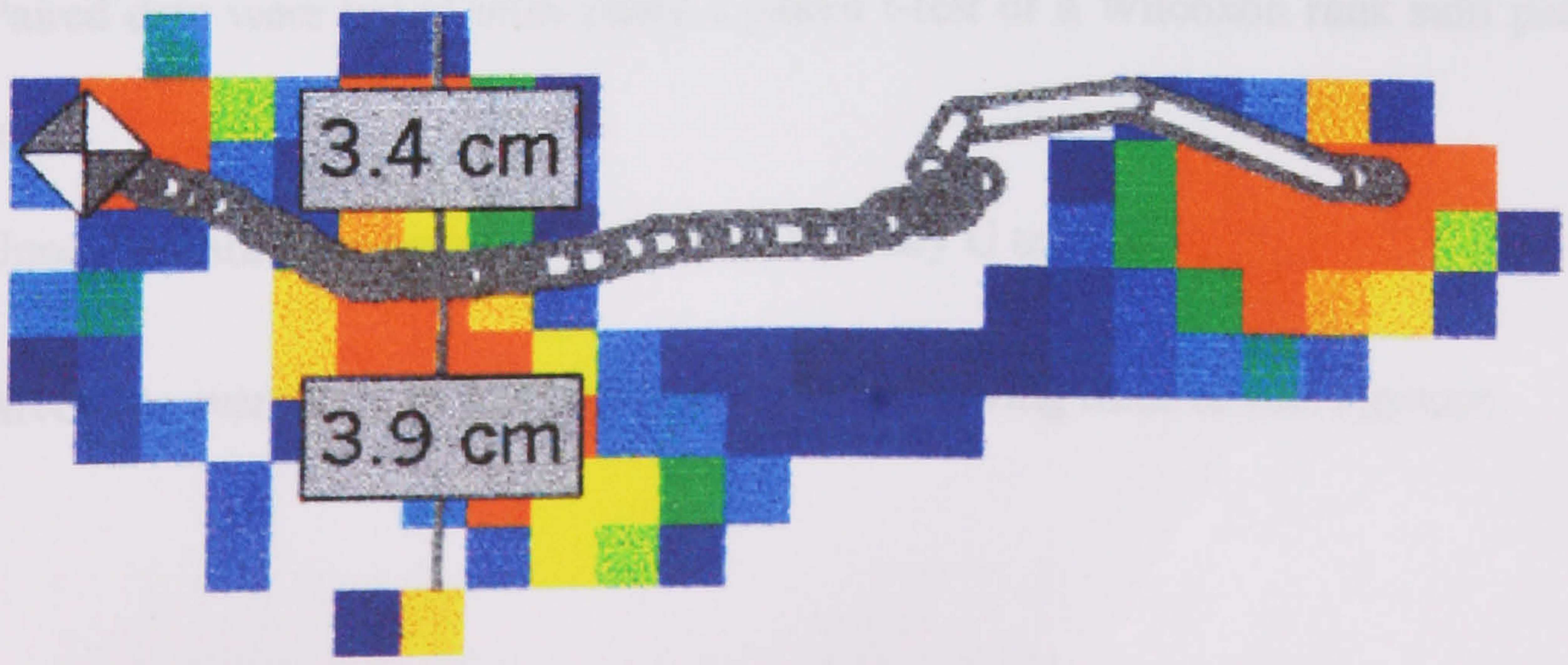
The time duration of the total contact phase was measured to compare the variability between footprints.

Figure 70. Using the pressure Vs time graph for each footprint to calculate the time from initial contact to peak pressure at each area.



The centre of force trajectory was used to provide an index of the medial – lateral positioning of the force for each print (D'Amico 1998 32/id; Cornwall and McPoil, 1997). The distance from the medial edge of the foot to the centre of force trajectory was measured across the metatarsal heads. The distance form the lateral side of the foot to the trajectory was measured. The medial / lateral value was calculated with values of less than 1 indicating that the pressure was borne on the medial side of the foot and values greater than 1 indicating that pressure was borne towards the lateral side (see figure 71).

Figure 71 showing measurement from medial and lateral to the centre of force trajectory.



The method of measuring the peak plantar pressure, timings and the COP index was accepted after testing for both intraobserver and interobserver repeatability (see Appendix VII). In the repeatability studies, the measurements were repeated five times for each footprint and no significant differences between the repeats were found. Observation of the repeated data showed that most of the variation in measurement occurred within the first three measurement sessions. Therefore to improve accuracy in the main study, each footprint was measured three times and the mean of the three repeats was used in the data analysis.

5.4 Data analysis

◊ The 1 sample Kolmogorov-Smirnov test was used to test the discrepancy between the set of values provided and the theoretical, normal distribution. A probability value of $p<0.05$ was chosen to represent the level at which the hypothesis (the sample was drawn from a normal distribution) was rejected.

◊ Continuous data with a normal distribution were tested using parametric tests. Non-normal data, interval or dichotomous data were tested using non-parametric tests.

◊ Paired data were tested with either a paired t-test or a Wilcoxon rank sum paired test.

◊ Unpaired data were tested with a Mann-Whitney U test.

◊ ANOVAs were used to test for comparisons involving three or more groups.

◊ Relationships between two variables were tested with Pearson or Spearman correlation.

5.5 Results

A total of 71 children were included in the study. Data were missing on 10 children because the system failed to identify their recordings. The group included 35 males and 26 females. The 61 children had a mean age of 10 years (SD = 2.65 years, range 5-15 years), LLAS mean = 5.82 (SD = 2.84, range 0-11), Beighton score mean = 3.8 (SD = 2.59, range 0-9) and HA angle mean = 6.82° (SD = 5.95°, range 8° varus - 26° valgus).

The collected data were tested for normality of the distribution. Table 29 shows that not all data were normally distributed. Figure 72 shows the frequency histograms and probablity (Q-Q) plots (see footnote[2]) for the abnormal distributions of the data on timings of heel contact to central metatarsal loading (HC-CENT) and total stance phase (HC-TO) and the measurement of 1st ray movement (1st Ray).

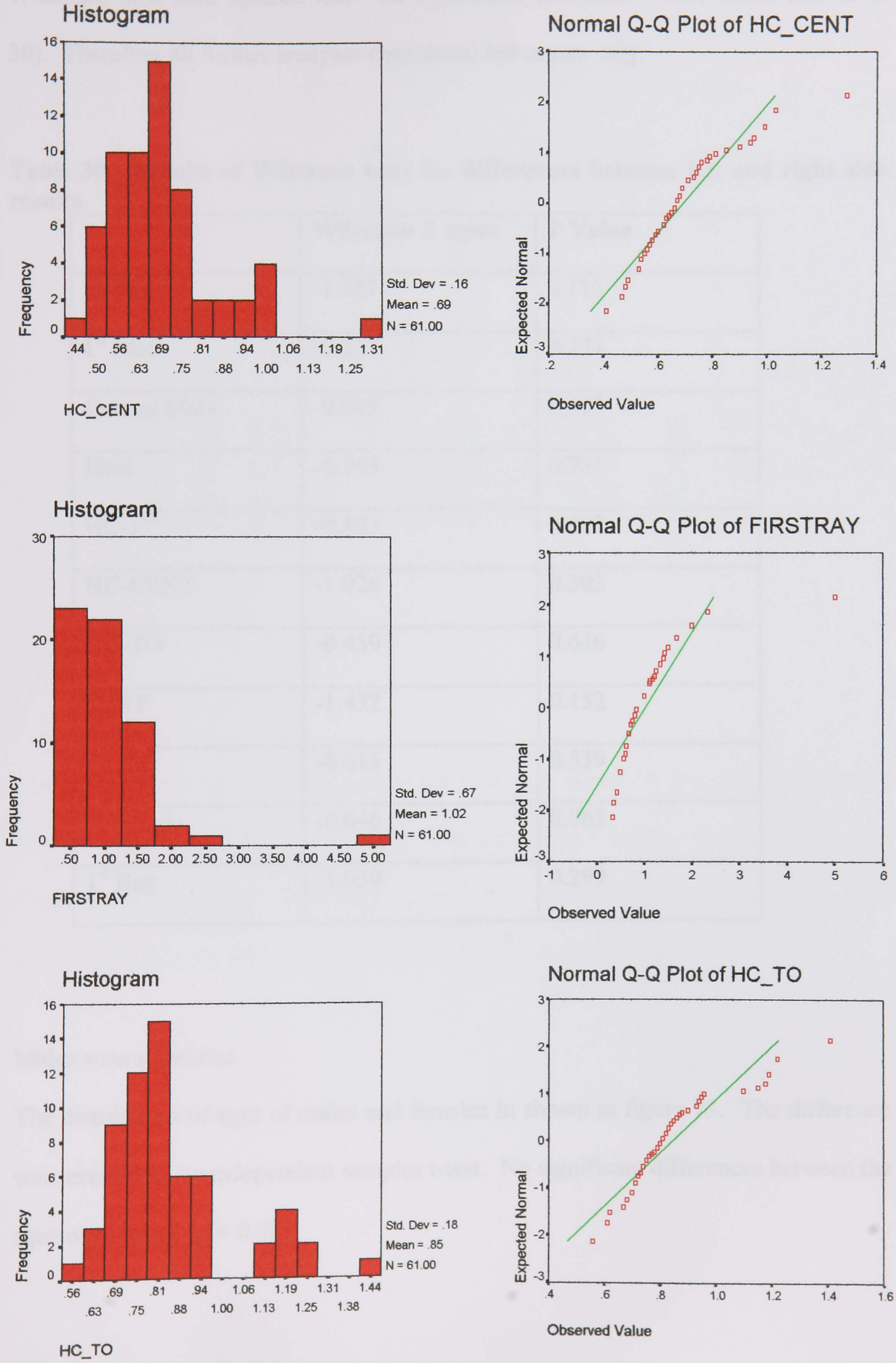
Since some of the data were not normally distributed, non-parametric tests were applied when considering that data.

Table 29. Kolmogorov-Smirnov test results

	Kolmogorov-Smirnov Z	P value
Hallux	0.832	0.492
1st Met	1.008	0.261
Central Mets	1.276	0.076
Heel	0.791	0.559
HC-1ST	0.741	0.641
HC-CENT	1.338	0.056
HC-TO	1.338	0.056
CO F	0.65	0.792
Age	0.838	0.484
Beighton score	1.196	0.114
LLAS	1.158	0.137
HA angle	0.727	0.663
1st Ray	1.455	0.029

[2] Probability plot is similar to the quantile-quantile plot. The quantile for one data set are compared to the quantiles of a theoretical distibution. A quantile is the fraction or percent of points below the given value (eg. the 0.3 (30%) quantile is the point at which 30% of the data fall below that value)

Figure 72. Frequency histograms and probability (Q-Q) plots (see footnote 2) showing non-normal distributions



The differences between left and right foot measurements were tested using a Wilcoxon rank sum squared test. No significant differences were found (see table 30). Therefore all further analyses considered left scores only.

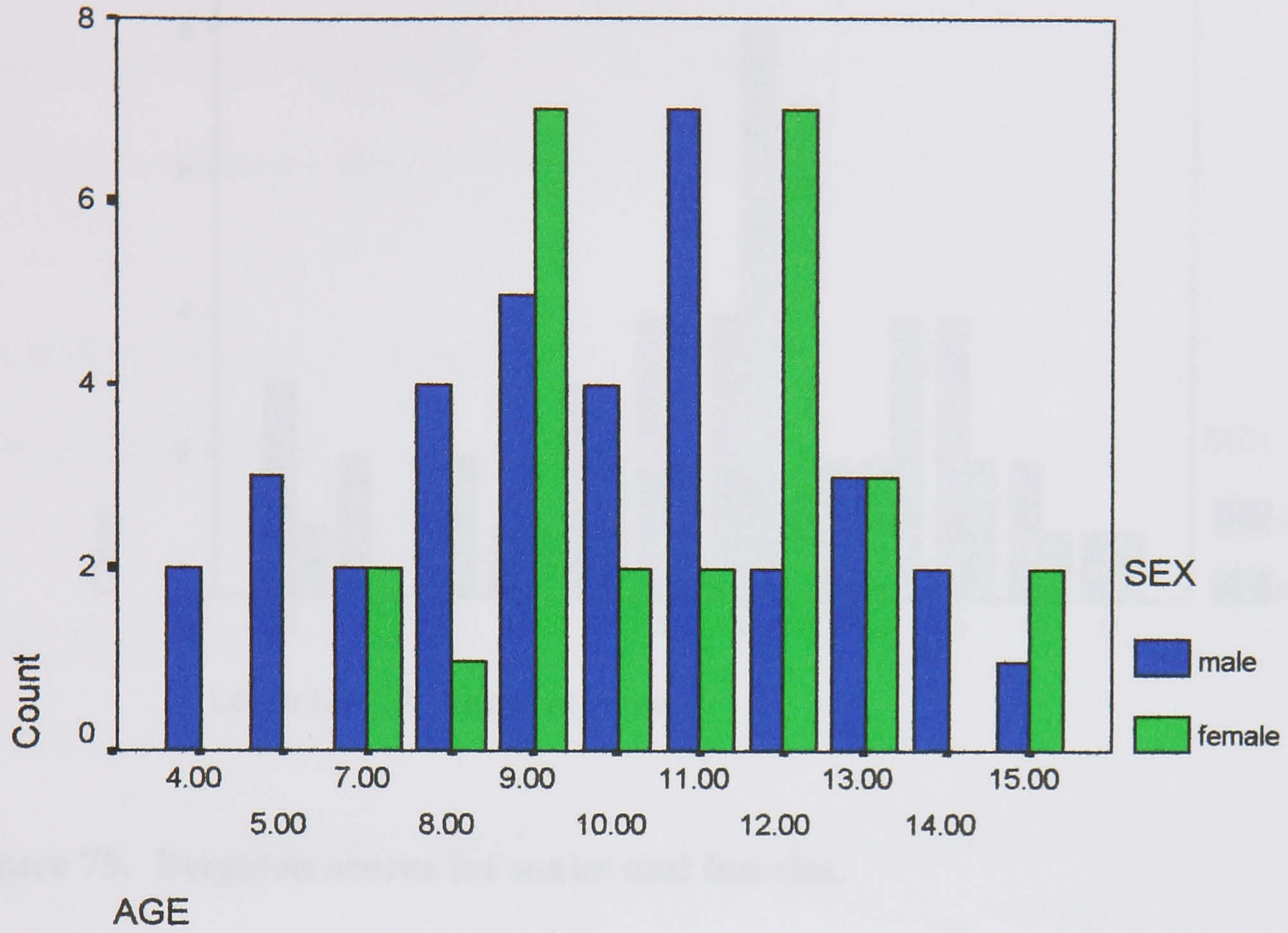
Table 30. Results of Wilcoxon tests for differences between left and right side results.

	Wilcoxon Z score	**P Value**
Hallux	-1.587	0.113
1st Met	-0.353	0.724
Central Mets	-0.085	0.933
Heel	-0.343	0.731
HC-1ST	-0.803	0.422
HC-CENT	-1.026	0.305
HC-TO	-0.459	0.646
C of F	-1.432	0.152
LLAS	-0.615	0.539
HA angle	-0.046	0.963
1st Ray	-1.039	0.299

Males versus females

The distribution of ages of males and females in shown in figure 73. The difference was tested with an independent samples t-test. No significant differences between the ages were found ($p = 0.08$).

Figure 73. Bar chart showing the distribution of ages between the males and females.



The distributions of flexibility scores are shown in figure 74 and 75. Differences between males and females were tested with independent samples t-tests. Despite the females having higher flexibility scores, no statistically significant differences between the sexes were found (Beighton score: $p = 0.68$, LLAS: $p = 0.53$).

Figure 74. Lower Limb Assessment Score for males and females.

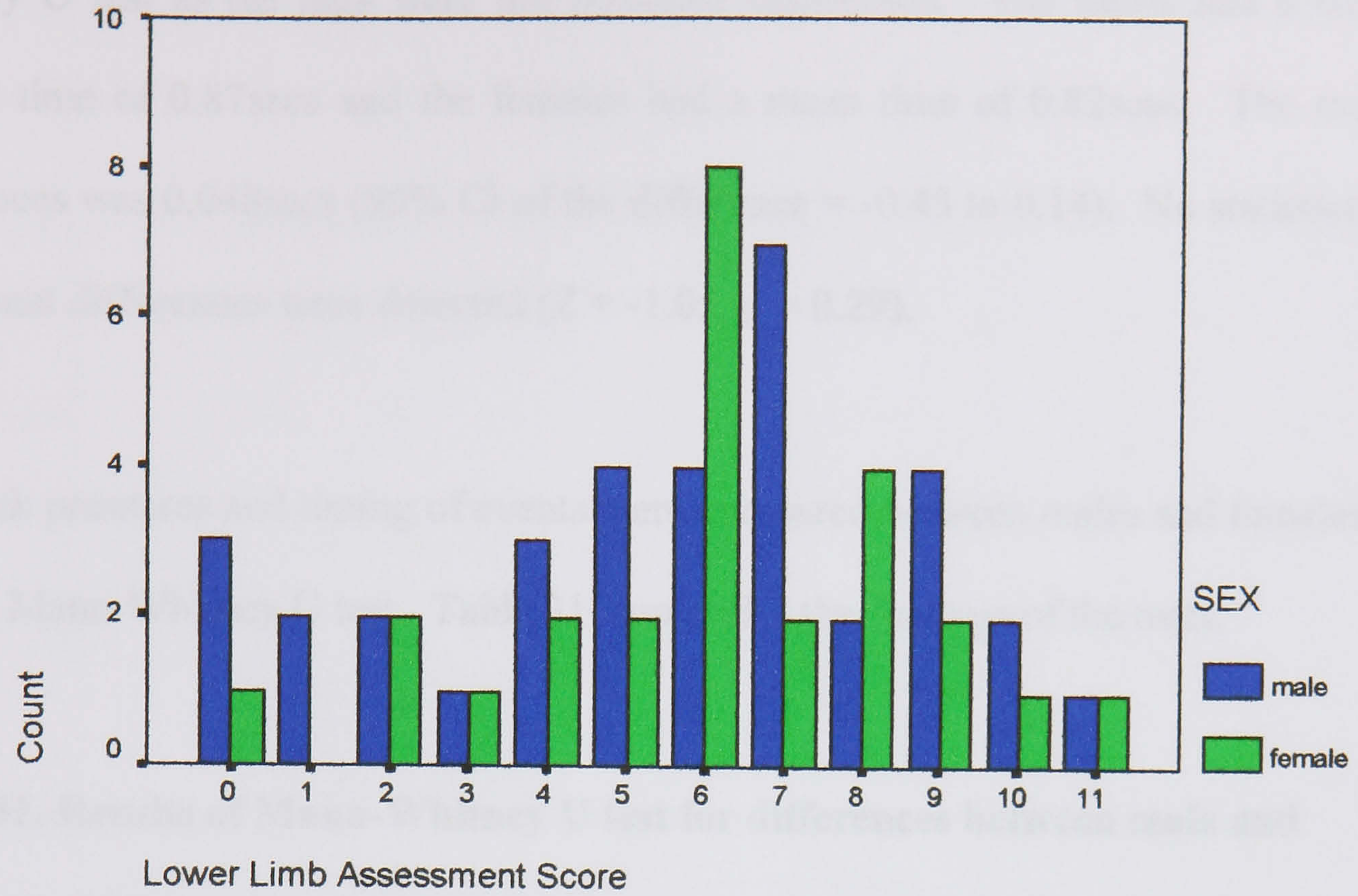
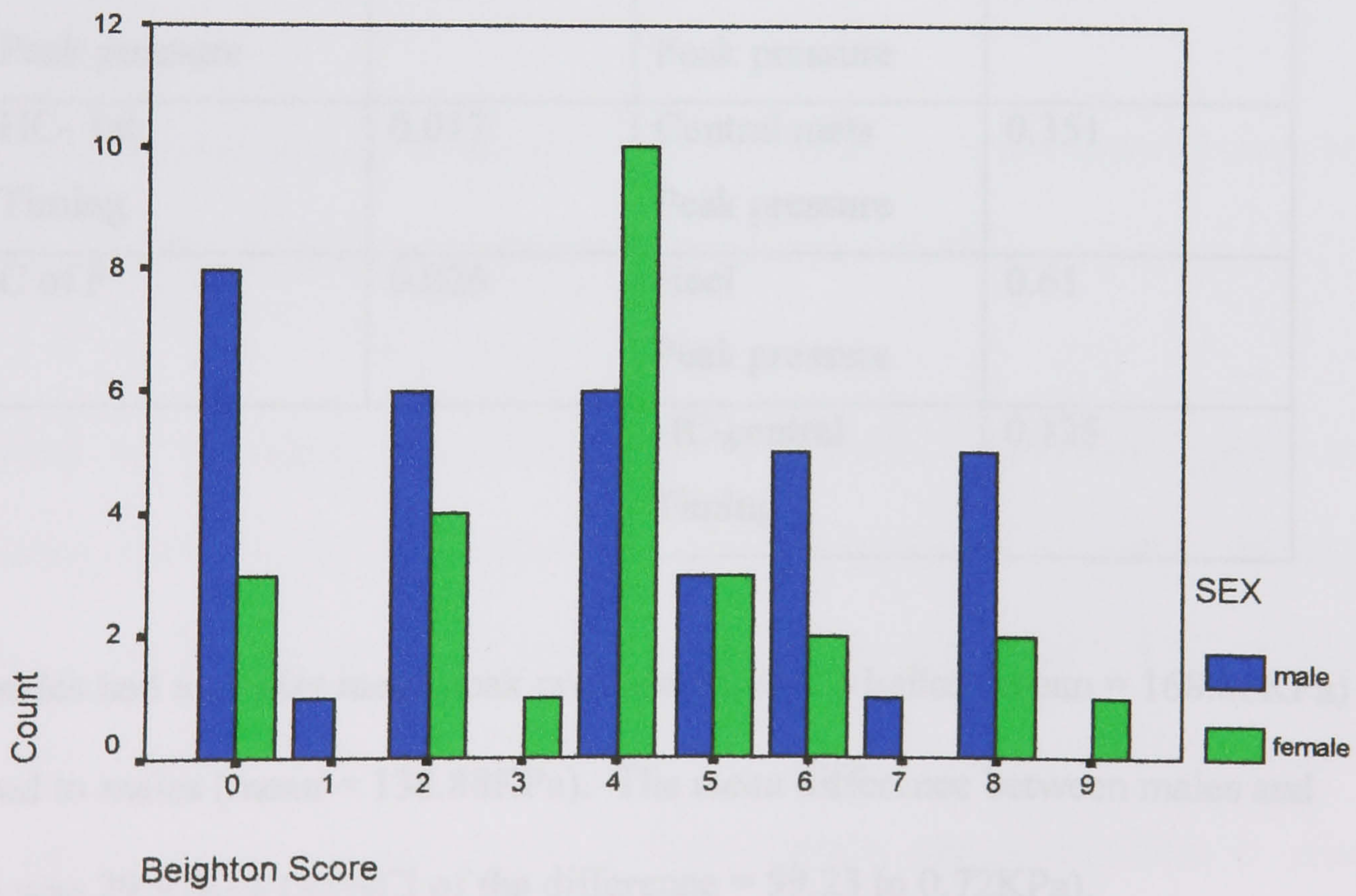


Figure 75. Beighton scores for males and females.



To investigate whether the males and females were loading the force plate in a similar fashion, the contact times on the plate were considered. The times from heel contact to toe-off (HC-TO) were compared between males and females using a Mann-Whitney U test as the data were not normally distributed. The males had a mean contact time of 0.87secs and the females had a mean time of 0.82secs. The mean differences was 0.048secs (95% CI of the difference = -0.43 to 0.14). No statistically significant differences were detected (Z = -1.05, p = 0.29).

The peak pressures and timing of events were compared between males and females using a Mann-Whitney U test. Table 31 summaries the findings of the tests.

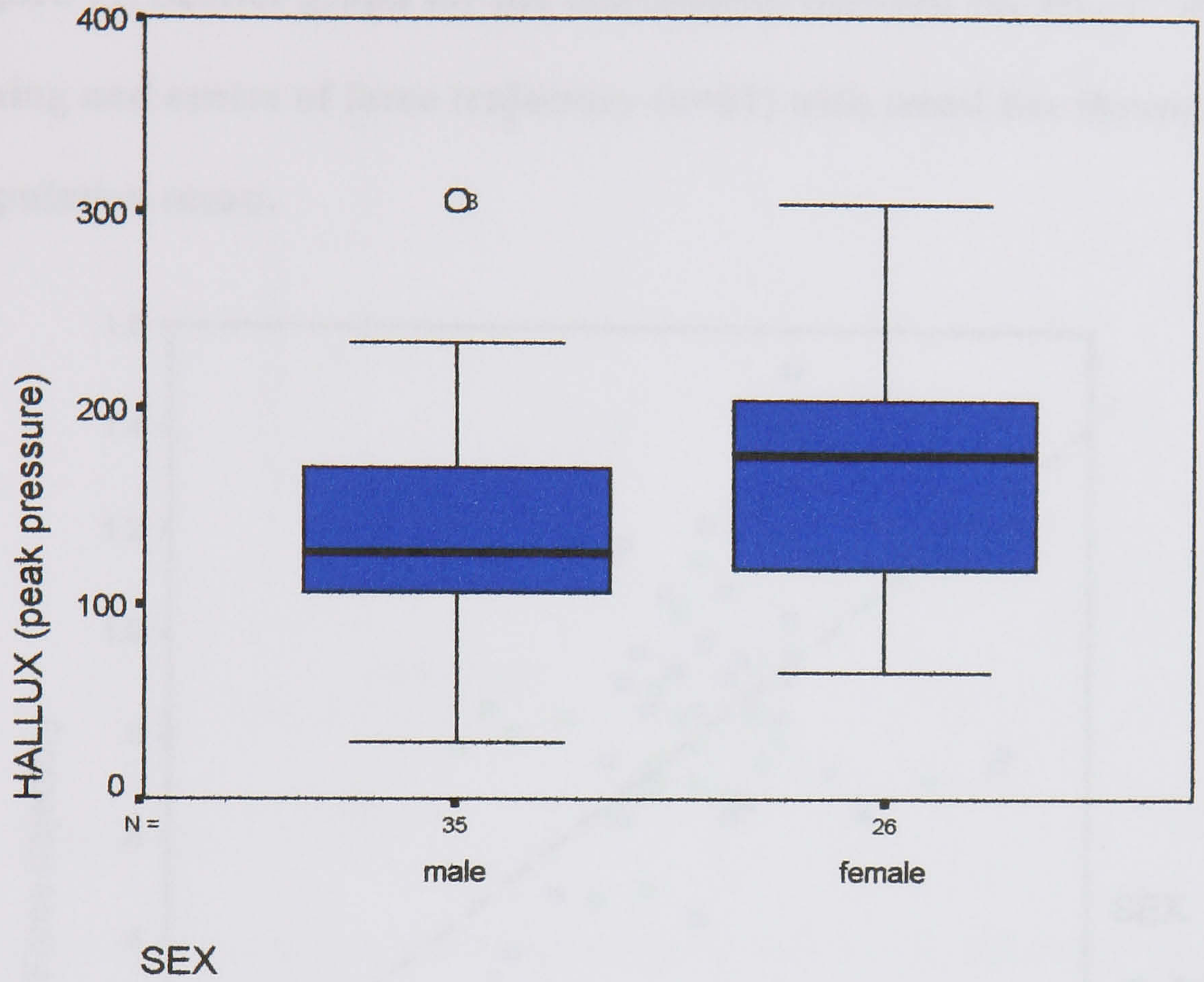
Table 31. Results of Mann-Whitney U test for differences between male and female measurements.

Significant results	**P value**	**Non significant results**	**P value**
Hallux Peak pressure	0.043	1st met Peak pressure	0.965
HC- 1st Timing	0.017	Central mets Peak pressure	0.351
C of F	0.026	Heel Peak pressure	0.61
		HC-central Timing	0.125

The females had a greater mean peak pressure under the hallux (mean = 168.86KPa) compared to males (mean = 138.88KPa). The mean difference between males and females was 29.97Kpa (95%CI of the difference = 59.23 to 0.72KPa).

Observation of the box plot in figure 76 shows that there was one male with an abnormally high value. With that variable removed, the differences in pressures became more statistically significant (p = 0.023).

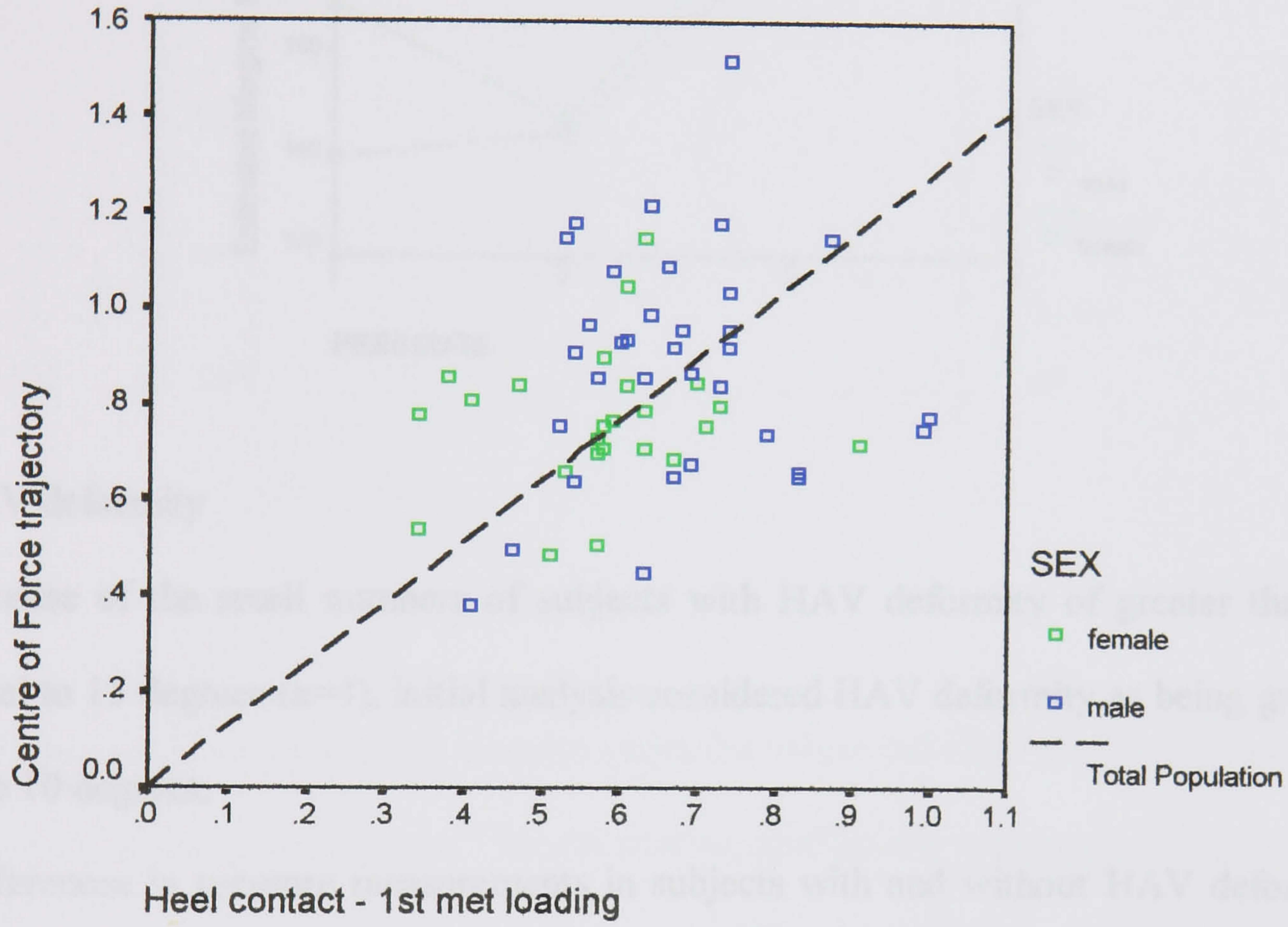
Figure 76. Box plot showing the differences in male and female peak pressures under the hallux.



All other anatomical areas (1st metatarsal, central metatarsal, heel) measured showed no significant differences between males and females ($p > 0.351$).

The timing of the phase from initial contact to the 1st metatarsal peak was significantly faster in females (mean = 0.58secs) compared to males (mean = 0.67secs), mean difference = 0.087secs (95% CI of the difference = 0.02 to 0.15). The position for the centre of force trajectory was significantly medially placed in females (mean = 0.78) compared with a more centrally placed trajectory in males (mean = 0.89). The mean difference = 0.11 (95% CI of the difference = 0.007 to 0.22), so an association between the timing to loading for the 1st metatarsal (HC –1ST) and the centre of force trajectory was sought. Figure 77 shows the scatter plot for the two variables.

Figure 77. Scatter graph for the relationship between the HC-1St metatarsal head timing and centre of force trajectory (n=61) with trend line through the population mean.



A Pearson correlation was undertaken to measure the strength of the association. No significant association was found ($r = 0.2$, $p = 0.13$). The association was no stronger when females were considered separately.

The 1st ray position, if plantarflexed, may also cause the 1st metatarsal to load more rapidly. No association between the 1st ray position and heel contact – 1st met loading was found (Spearman correlation $r = -0.09$, $p = 0.5$). There was no difference in 1st ray position between males and females when tested using a Mann-Whitney U test ($Z = -0.966$, $p = 0.33$).

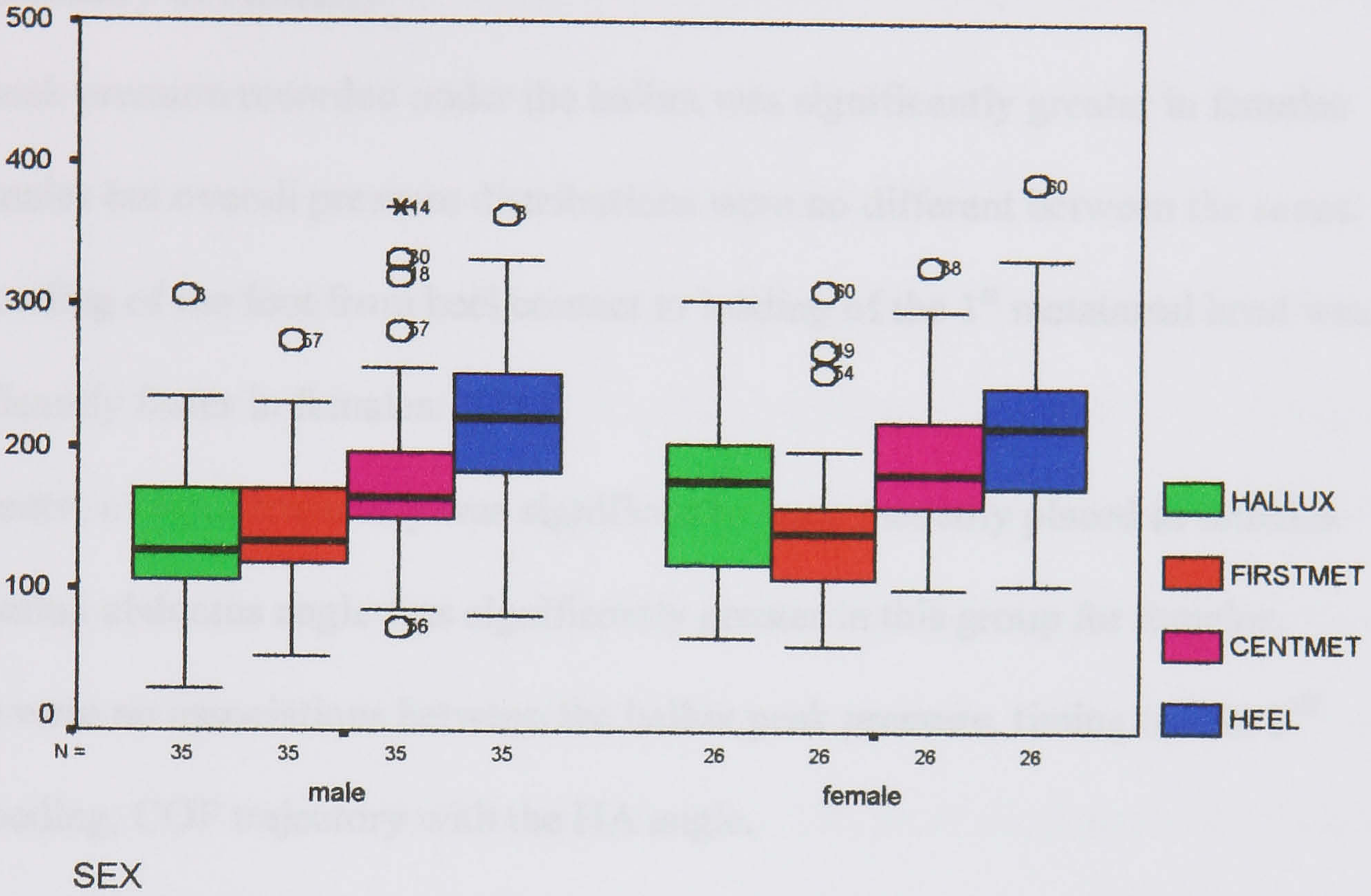
Females had a significantly greater HA angle (mean = 9.85°) compared to males (mean = 4.57°, mean difference = 5.27° (95%CI of the difference = 2.49 to 8.06°). Associations between the three significant results (hallux peak pressure, timing of HC-1st, centre of force trajectory) with HA angle was tested with Pearson correlation. No significant associations were found ($r < 0.2$, $p > 0.11$).

The distribution of pressure showed some differences between males and females (see table 32) but observation of figure 78 suggested that the differences between most areas of the feet were small except for the difference between pressures under the hallux which was large, with the pressure under the female hallux being almost 20% greater than under the male hallux. .

Table 32 showing distribution of pressure measurements (KPa) across the forefoot

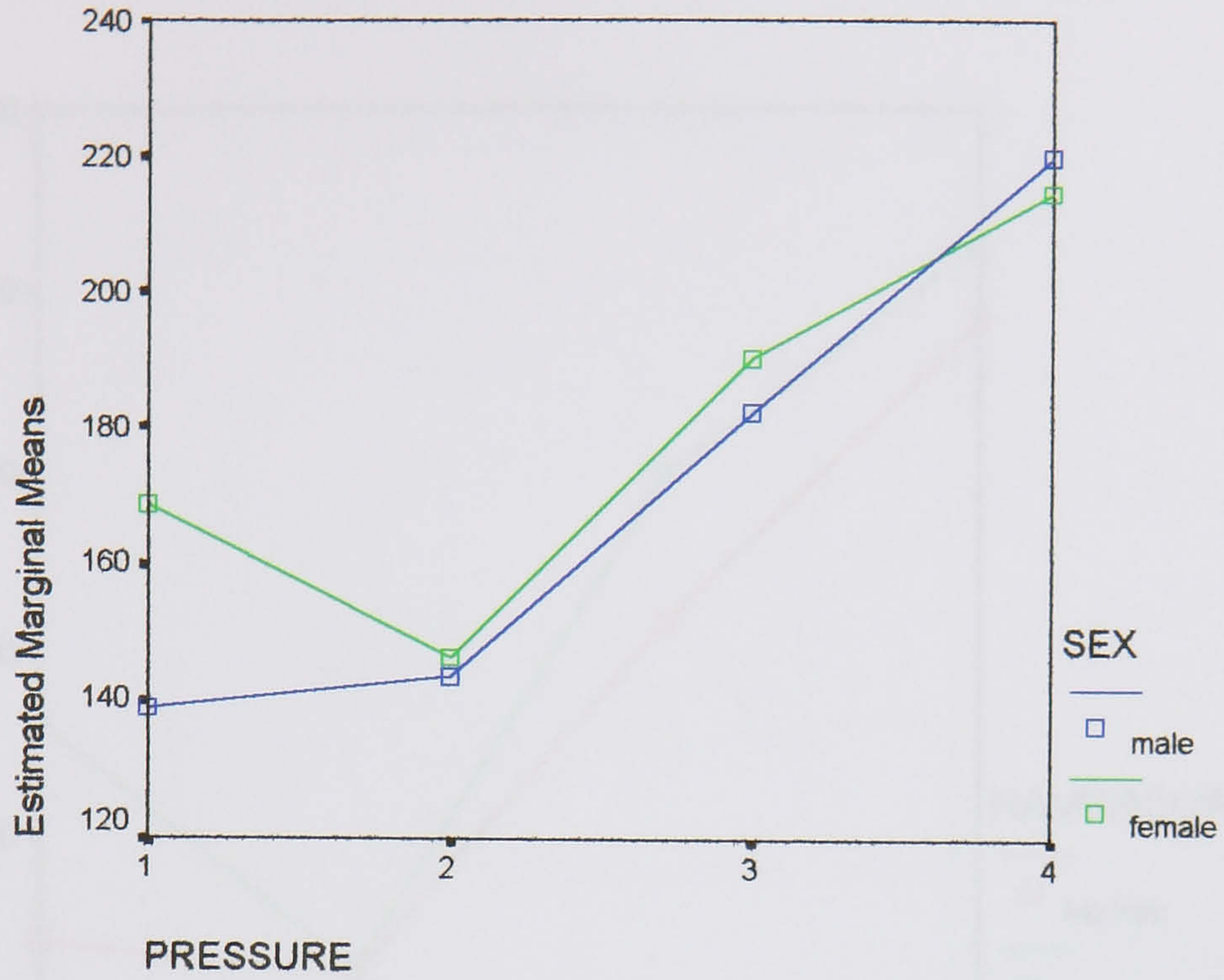
	Hallux (1)	**1st Met (2)**	**Central mets(3)**	**Heel (4)**
Males	138.88	144.00	182.94	220.33
Females	168.86	146.54	190.73	214.80

Figure 78. Clustered box plots showing the relationship between gender and foot pressure distribution.



The difference in pressure distribution was tested for significance using a mixed Ax(B) ANOVA. Within subject tests showed significant differences in pressure measurements at the four sites ($F(3,59) = 30.18$; $p < 0.001$) but no significant interaction between sex and pressure ($F(3,59) = 1.60$; $p = 0.12$). Tests for between subject effects showed no significant differences in the distribution ($F(1,59) = 0.59$; $p = 0.45$). This was confirmed with observation of the profile plot that shows the patterns mirrored for the different genders (see figure 79)

Figure 79. Profile plot for the interactions between pressure measurements and gender.

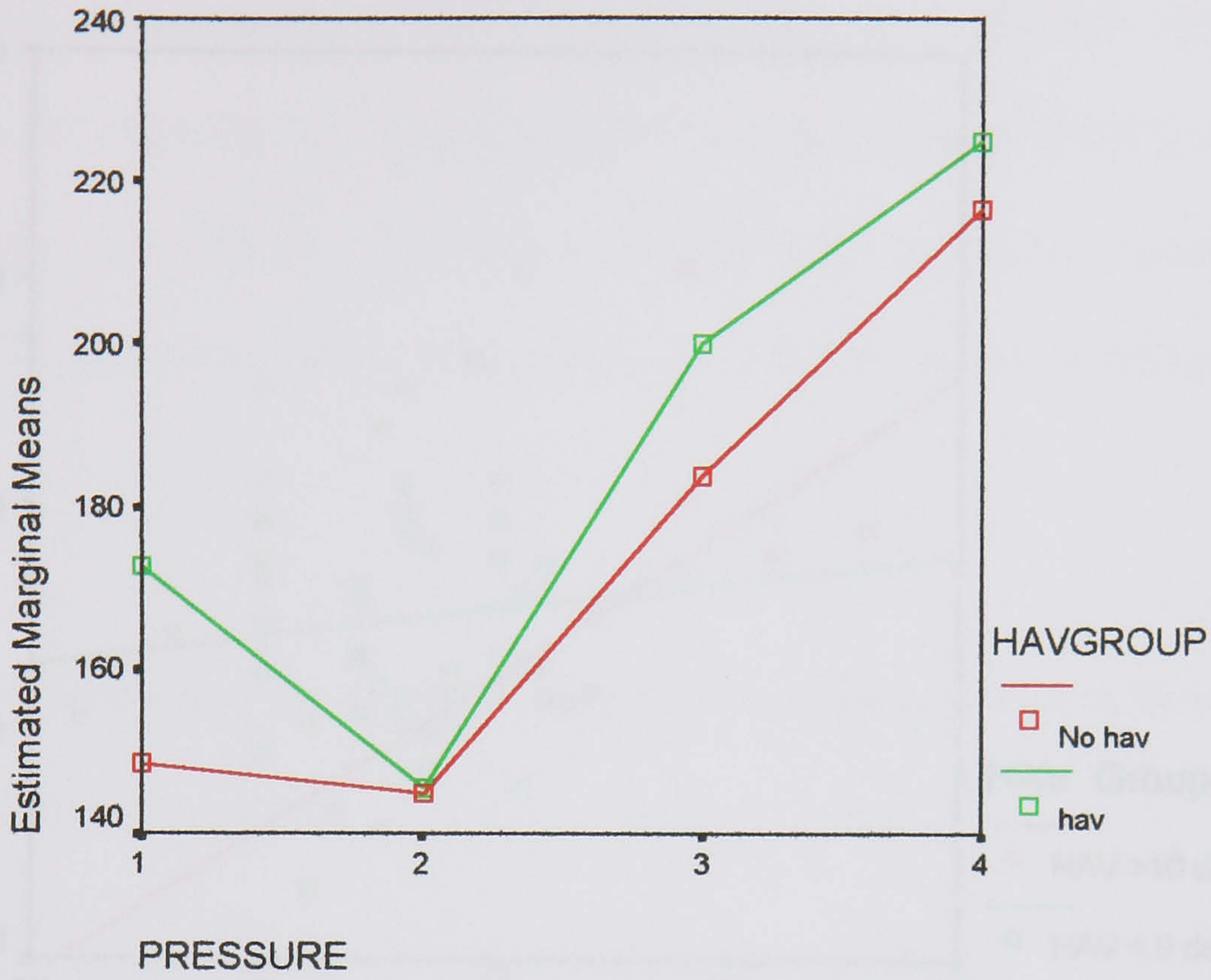


HAV deformity

Because of the small numbers of subjects with HAV deformity of greater than or equal to 15 degrees (n=4), initial analysis considered HAV deformity as being greater than 10 degrees.

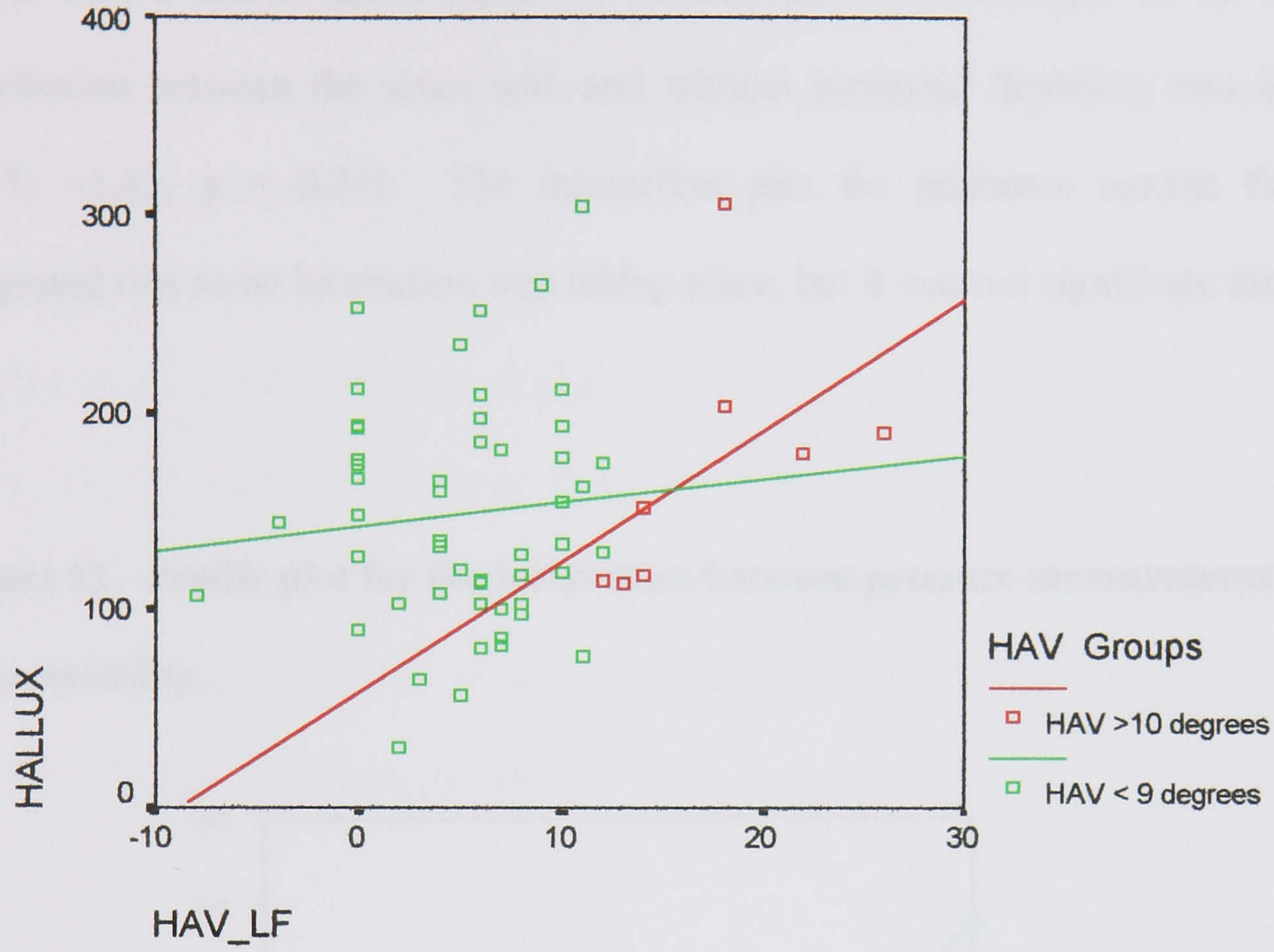
Differences in pressure measurements in subjects with and without HAV deformity (>10°) were also tested with a mixed factor (AxBx(C)). No difference in pressure distribution was found between the sexes with and without HAV deformity (F (1,57) = 0.34; p = 0.56). The interaction plot for pressures in subjects with and without HAV deformity (>10°) is shown in figure 80. Of note, only 8 subjects had HAV deformity of > 10°).

Figure 80. Profile plot for the interactions between pressure measurements and HAV deformity.



The association between peak pressure under the hallux and HAV deformity was considered through correlation. The correlation coefficients were measured for HA angles of greater than and less than 10 degrees. The associations are shown in figure 81. For HA angles of greater than 10 degrees, a positive correlation was seen ($r = 0.5$) but the coefficient was not significant ($p = 0.2$) which may relate to the small sample size.

Figure 81. Scatter plot showing the association between peak pressure under the hallux with HA angle for the HAV group versus no HAV, for the definitions of HAV as >10°.

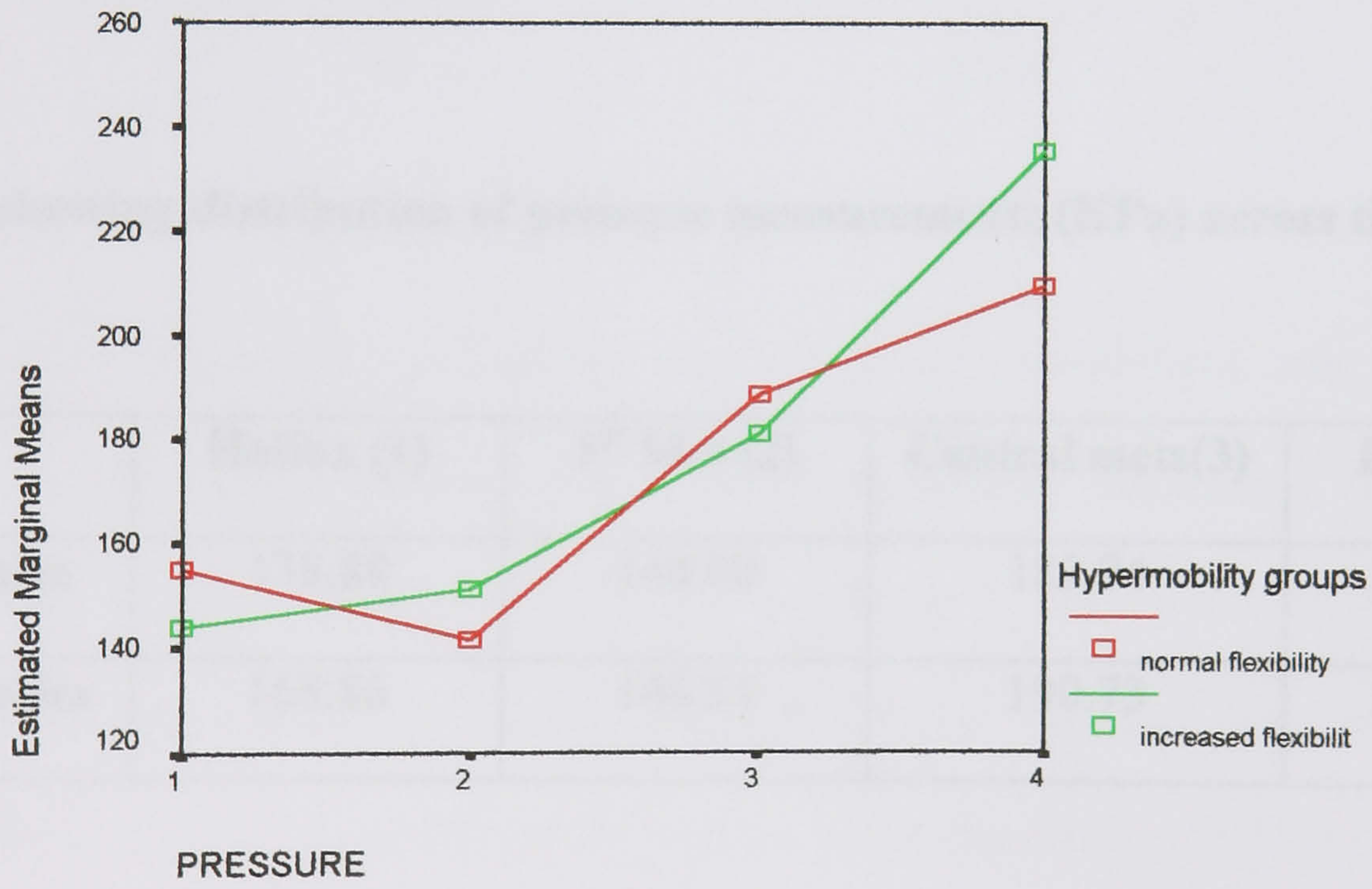


When analysis was undertaken for HA angles of >15 degrees, significant differences in the hallux peak pressure were found between the no HAV and HAV groups (Z = -2.73, p = 0.023). There were no significant differences in the timings from heel contact –to 1st met loading (Z = -0.47, p = 0.66), heel contact to central met loading (Z = -0.22, P = 0.83) or heel contact to toe – off (Z = -0.38, p = 0.71). There was no evidence of a difference in the 1st ray position (Z = -0.57, p = 0.57) but the COF trajectory was more medially displaced in the HAV >15 degs group (Z = -1.92, p = 0.054).

HYPERMOBILITY

Differences in pressure measurements in male and female subjects with increased flexibility (LLAS >8/12) and normal levels of flexibility (LLAS <7/12) were also tested with a mixed factor ANOVA (AxBx(C)). No difference in the pressure distribution between the sexes with and without increased flexibility was found (F (1,57) =1.43; p = 0.24). The interaction plot for pressures against flexibility suggested that some interaction was taking place, but it was not significant (see figure 82).

Figure 82. Profile plot for the interaction between pressure measurements and hypermobility.



The association between the high pressure seen in the hallux in females was investigated with regard to the flexibility score. Using Pearson correlation, no association was found (r = 0.12, p = 0.78). When only children considered hypermobile (LLAS = 8 or greater) (n=17) were considered, the association between hallux pressure and flexibility score increased ($r = 0.41$) but was still not statistically significant ($p = 0.1$). There was no association between the flexibility score and the COF trajectory ($r = 0.11$, $p = 0.67$).

5.51 Summary of Findings

- The peak pressure recorded under the hallux was significantly greater in females than males but overall pressure distributions were no different between the sexes.
- The loading of the foot from heel contact to loading of the 1^{st} metatarsal head was significantly faster in females.
- The centre of force trajectory was significantly more medially placed in females
- The hallux abductus angle was significantly greater in this group for females.
- There were no associations between the hallux peak pressure, timing of HC-1^{ST} met loading, COF trajectory with the HA angle.
- The pressure distributions under the feet were no difference when HAV deformity was present.
- Increasing flexibility did not appear to be associated with the increased pressure under the hallux.

5.6 Discussion

This study found that the pressure under the hallux was significantly greater in females that in males. There were no significant differences in pressure measurements under the metatarsals or the heel between males and females. Hennig (1994) also reported that the pressure under the hallux was greatest in females. In females a peak pressure of 253KPa was found compared to 238KPa in males. This difference was not tested for statistical significance, but no other area of the foot was seen to have differences as great. All other differences were less than 9KPa. Like this study, Hennig's study also considered children (6-10 years old). The pressure measurements by Hennig were greater than recorded in this study (253KPa versus 169KPa) which may be due to the different techniques used (walking at self-selected slow speed) and different equipment (EMED platform). Both studies used the mean of 5 recordings. Hennig also had a greater number of children (n=125) compared with the present study. In their dynamic study of 74 adults aged 18-30 years old using the Musgrave force plate, Bennett and Duplock (1993) also found that the hallux showed greater peak pressures in females compared with males. In all other locations, the male feet showed greater peak pressures than females. The distribution of pressure patterns was reported not to differ between the sexes although statistical tests were not applied. The differences in peak pressures at the hallux for males and females were not tested for statistical significance. The peak pressures at the hallux had a mean pressure of 3.5Kg/cm^2. This equates to 343.35KPa (1Kg/cm^2 = 98.1KPa) which was greater than recorded by Hennig or the present study and is most likely due to the greater weight of the subjects (adults versus children). Holmes *et al* (1991) also showed higher peak pressures under the hallux in females when comparing 10 males to 10 females of mean age 30 years. Using the Pedobaragraph with a set cadence for 5 repeated trials, the females showed a peak pressure under the hallux of 4.2Kg/cm^2 compared to 3.8Kg/cm^2 in males. The readings are of a similar magnitude to the trial by Bennett and Duplock. Again, the statistical significance of the difference was not tested. The reason for the difference in pressures under the hallux has not been examined in any other study. The high pressure recorded in the hallux of women would suggest that some functional differences occur during walking but it is unclear from the present study why they are occurring. It is quite possible that in all the previous studies, as in this study, the HA angle was greater females than males and thus the difference in pressure seen under the hallux is as a result of the abducted hallux. Kernozek *et al* (2003) reported increased peak pressures under the hallux in their HAV group. However, in this study other male-female differences were found that may demonstrate a difference in foot function between males and females.

The differences in the peak pressures in other areas of the foot did not show male to female differences suggesting that the functional difference were very localised. The pressure distribution across the forefoot in this study showed that the central metatarsals took the greatest weight, followed by the hallux and then the first metatarsal in females but the 1st metatarsal took greater peak pressure than the hallux in males. Both these patterns showed agreement with other studies. The female pressure pattern was similar to that described by Holmes *et al* (1991) and Bennett and Duplock (1993). The pattern found in this study for males was similar to the standing measurements of Cavanagh *et al* (1987), Hutton and Dhanendran (1990), and to the male sample in Bennett and Duplock's study. Agreement with all published studies was not expected due to the differing methods used in respect of equipment (force plate / insoles), method of dividing the foot into different regions and the method of loading the foot. In this study, the pressure measurements were taken from the initiating footstep whereas other studies usually took a mid-walk footprint. The method in this study was chosen for ease of use with children. Using the first footstep prevented problems with children trying to judge their stride in order to make contact with the pressure mat. It is recognised that the initiating foot pressures may not represent the foot pressures that would be seen with continuous walking. Only one study was found that has investigated the difference between first or continuous steps, finding the one step method was more reliable (Peters et al., 2002).

The distribution of pressure across the forefoot was not significantly different between males and females in this study. The differences in foot function were found in the timing variables measured and centre of force trajectory position. Significant differences between males and females were seen for the timing of heel contact to 1st metatarsal head loading. These were significantly faster in females by around 0.09 seconds. It is difficult to judge whether this figure is clinically significant. Given that the total contact time was 0.85 seconds (mean), such a difference would represent 11% of the total contact time. There was no significant difference between the total contact times of the male and females in the study ($p = 0.29$) but if females were loading the 1st metatarsal quicker than the males, they must therefore be spending a longer time on the medial forefoot region (either the 1st metatarsal or the hallux) than the males. The greater pressure seen under the female hallux applied over a greater time, repeated for on every step might be sufficient to cause the development of HAV deformity. It could be hypothesised that those with predisposing factors such that allow the hallux to become unstable in the direction of abduction – for example if a metatarsus adductus deformity or metatarsus primus varus deformity is present - would develop the deformity early in life. Women with a more stable 1st metatarsophalangeal joint may only develop the deformity in later life. In this study, the greater peak pressures under the hallux in females were recorded on the first step of gait. The study would need to be repeated in order to determine whether the result is the same for each step of gait.

Only one other study was identified that considered the timing of events in the gait cycle. Betts *et al* (1991) found that the 1st metatarsal loaded earlier than the 2nd metatarsal in their adult population, but did not look for male and female differences. The centre of force trajectory showed significant differences in position in females compared to males ($p = 0.026$). In the females the trajectory was more medially placed so the forces being placed through the foot would be greater along the medial column. This may account for the more rapid loading of the 1st metatarsal head seen in females since normally the centre of force would progress along the lateral border of the foot after heel contact, crossing the metatarsals from 5th to 1st as the forefoot loads before propulsion occurs through the hallux. By placing the weight initially along the lateral border of the foot, the calcaneocuboid joint should become stable, creating a strong pulley for the action of peroneus longus muscle to stabilise the 1st metatarsal against the ground for propulsion (Root et al., 1977a). If the weight is not taken laterally, the locking mechanism of the calcaneocuboid joint may not occur and the 1st metatarsal will become unstable. Cornwall and McPoil (1997) noted that it was not possible to relate the mechanics of the foot to the centre of pressure index and thus the impact of the medial positioning of the trajectory can only be speculated upon.

Abnormal flexibility (hypermobility) may be such a factor that makes the 1st metatarsophalangeal joint unstable and may cause the centre of force to be medially placed. For example, hypermobility is associated with poor proprioception and increased foot pronation. The lack of spatial awareness of the joint position may lead to the foot pronating in order to gain a greater surface contact area with the ground and thus greater feedback of position in space. Further, the ligament laxity may cause arch collapse and this lead to greater foot pronation. In both these situations, it may be expected that the centre of force trajectory wil be placed more medially. As discussed in chapter 4, there is some difficulty in determining "hypermobility" as it is inappropriate to set a single cut-off point where a continuum of increasing laxity exists. However, in this study a lower limb assessment score of 8/12 was used to describe a level at which the level of flexibility could be considered abnormal (ie. hypermobile). In this study, no association between the centre of force trajectory and hypermobility score was found ($r = 0.11$) and the pressure distribution was not influenced by whether a subject had increased flexibility or not ($p = 0.24$). The interaction plot suggested that some effect was taking place and further investigation of the pressure distribution and increasing flexibility may be indicated using a larger study group. The association between the peak pressure under the hallux and the flexibility score increased from $r = -0.12$ to $r = 0.41$ when only children considered to be hypermobile (LLAS greater than 7/12) were included. However the number of children included was small (n=17) which may have influences the p value, which was not significant (p=0.1). Hypermobility is reported to occur predominantly in women (Beighton et al., 1973) but in this study there were no differences in flexibility scores between males and females. This may have been due to the narrow age range of children used and any association between gender, hypermobility and peak pressure or the position of the COF may have been masked.

The first ray position has been previously associated with juvenile hallux abductovalgus when a plantarflexed position of the 1st metatarsal was noted (Kilmartin et al., 1991). Theoretically, a plantarflexed 1st metatarsal would also lead to early loading of the 1st metatarsal as the lowered position of the metatarsal would bring it into ground contact sooner than would occur with a more raised metatarsal. In this study, no association between the timing from heel contact –1st metatarsal and the HA angle was found. Despite earlier studies suggesting that the Sagittal Ranger used to measure first ray position was a reliable device, it was felt during this study that the Ranger was not identifying the first ray position well. A plantarflexed first ray rests in a plantarflexed position. When the Ranger is placed along the metatarsal heads, it places the first ray into dorsiflexion, level with the other metatarsals. Movement is measured from this level position. In theory, a plantarflexed first ray would have less dorsiflexion from the level position because it would have used up some of the motion in becoming level. It would have a good range of plantarflexion available so the overall index created (dorsiflexion/plantarflexion) would be less than 0 to indicate a plantarflexed 1st ray. Because the 1st metatarsal is larger than the lesser metatarsals, even a neutrally placed 1st metatarsal will have to be slightly dorsiflexed to place it on the measuring platform, skewing the results. It was also difficult to measure accurately the range of motion in very flexible children and identifying the end of range of motion was felt not to be accurate. A simple gauge of the resting position of the metatarsal may have been more useful than measuring the range of motion. As with identifying associations between the HA angle and other factors, since the study only had a very small number of children with HAV deformity, any association between 1st ray position, pressure and HA angle may not have been identified.

As expected, and despite the small number of children with HAV deformity (ie. >15 degs), there were significant differences in the HA angle between males and females ($p = 0.043$) and this may have accounted for the difference in hallux pressures recorded. However, the HA angle was found not to be associated with the greater peak pressure under the hallux in females when tested with Pearson r correlation ($r = 0.21$, $p = 0.11$). The studies by Kernozek *et al* (2003) and Blomgren *et al* (1991) found greater peak pressure under the hallux in their HAV groups compared to the control groups. Kernozek does not state the male to female ratios in the study groups. It may be that the HAV group consisted mainly of females and the control group had more males. In this situation, the increased pressures reported under the hallux may be as a result of the sex distribution rather than the HA angle. Betts *et al* (1991) found that peak pressure under the hallux was lower in the presence of HAV deformity. In this study, the association between pressure under the hallux and HA angle was seen to increase when only those with HAV deformity were considered ($p=0.5$) but care should be taken when accepting this relationship as only very small numbers of children were involved. A significant difference was also found in the position of the centre of force in children with HA angles $\geq$ 15 degrees and those with angles < 15 degrees. The centre of force was positioned more medially in the HAV group ($p = 0.054$). As mentioned previously, it is not possible to use the centre of force trajectory to describe the biomechanics of the foot. However, it is easy to visualise how the increased force placed through the medial side of the foot could be overloading the 1st metatarsophalangeal joint. An alternate view is that the hallux is no longer fully functional in HAV deformity. The weight transfer through the hallux is not possible in propulsion so the weight is passed medially onto the opposite foot causing the COF position to become more medially placed. Hence it is as a result of the HAV deformity rather than a cause. Stokes *et al* (1979) also reported that the centre of force (centroid) was more medially placed in HAV deformity but did not report this as a cause or effect.

The main limitations to this study were the size of the study group, particularly the number of children with HAV deformity. A retrospective power calculation for the total number of children included, accepting an alpha value of 0.05, gave a power of 0.5. Therefore there was a 50% chance of significant results not being detected. The pilot studies showed that the method of capturing the force plate data and the measuring technique from the output was reliable. The repeatability studies undertaken showed that the method of taking the measurements was repeatable (see Appendix VII). It was noted during repeatability testing that the variation in measurements between individual footsteps was large. For example, the pressure taken on the 1st metatarsal head could vary by as much as 100KPa. This would be between 50-75% of the pressure taken. It was not known how many steps would have to be recorded in order to see the variation in pressures reduce or whether every footstep is different. Having a large potential variation in measurements may obscure the underlying associations with other variables. If the study were to be repeated, an initial study to determine the number of steps required would be important. A benefit of the insole system with F-Scan is that multiple footsteps can be measured in one walk.

The validity of the force plate measurement was not tested but the results compared favourably with data reported in other studies. For example, the mean contact time for foot contact with the pressure mat was 0.87 (95%CI = 0.8 to 0.93) seconds for males and 0.82 (95%CI= 0.75 to 0.88) seconds in females. Hutton and Dhanendran (1990) reported a contact time from heel contact to metatarsal loading of 0.9 seconds. Hughes reported a contact time from heel contact to hallux loading of 0.8 seconds.

Although both these studies used adults and different equipment, the similar level of recording for this timing variable suggests that the method of recording the foot pressures in this study may be comparable. No study provided total contact time data for comparison. It had been previously reported that the speed of walking has a large impact on pressure readings (Zhu et al., 1995; Hennig et al., 1994) and that, in children, the speed did not affect the plantar pressures until the child was running. Since the mean contact time recorded in this study was similar to other studies, the speed the children were walking could be considered to have a minimal impact on the results.

No differences between left and right footprints were found suggesting that both feet function symmetrically and limb dominance does not influence foot loading. The girls were slightly older than the boys, but the difference was not statistically significant. The development of a mature gait is reported to occur around the age of 7 years old (Sutherland et al., 1980). The mean age of children in this study was 10.8 years for girls and 9.6years for boys and so the slight age difference would not be expected to affect gait parameters.

5.7 Conclusion

Differences between male and female children were shown with females having a significantly higher peak pressure under the hallux, significantly faster loading from heel contact to 1st metatarsal peak pressure and a more medially placed centre of force trajectory. The greater force placed on the female hallux during gait suggests functional differences occur between the male and female foot. Higher peak pressures under the hallux in female feet have been found in both adult and children studies: a more medially placed centre of force trajectory has been found in earlier studies that considered adults. Correlation analysis failed to show any statistically significant association between the variables although it was found that higher peak pressures under the hallux and a more medially placed centre of force trajectory occurred in children with HAV deformity. The association between hallux peak pressures and joint flexibility increased in hypermobile children. The numbers of children in this study with HAV deformity was small which may have prevented any associations being identified.

Males and females showed no difference in the distribution of pressures across their feet and joint hypermobility appeared not to affect the pressure distributions.

5.8 Publications and Presentations

- Is there a difference in male and female foot pressure measurements? An F-scan study in children. Submitted to the FIP world Congress, Boston August 2004.

CHAPTER SIX SYSTEMATIC REVIEW OF THE TREATMENTS FOR HALLUX ABDUCTOVALGUS

Introduction

A systematic review in hallux abductovalgus

Background

Aim

Objectives

Methods

Data Analysis

Results

Discussion

Conclusion

Publications

6. SYSTEMATIC REVIEW OF THE TREATMENTS FOR HALLUX ABDUCTOVALGUS

6.1 Introduction

Prior to undertaking a study in a specific field, it is common practice to undertake a literature search to identify articles of relevance. The area of interest may have been summarised previously and presented in the form of a literature (medical) review, written to conclude the current knowledge on a topic at that time. Mulrow (1987) described such reviews as "*subjective, scientifically unsound and inefficient*". This harsh description was based on the opinion that literature reviews may be undertaken in a haphazard way, without a firm strategy for identifying appropriate studies and without the reviewer defining how the articles for inclusion were chosen. For example, the article may not inform the reader if the reviewer had only included those trials that supported a particular opinion, whether the review was limited to include only articles from key books or journals, if an electronic search of specific dates had been undertaken or whether the review included all literature, published and unpublished, up to a defined date. A further problem with the medical review is that the studies included are rarely assessed for quality, or the quality is rarely assessed equally for all studies.

A medical review needs to state clearly its purpose so the readers can identify the relevance to themselves. If the purpose of the review is stated it will help determine the strategies needed to collect information from studies of the appropriate design. For example, reviews on etiology may require reports from case controlled studies; the natural history of a condition would be based upon cohort studies; treatment effects would be determined through clinical controlled trials (Mulrow, 1987). Table 33 lists some questions that should be asked when assessing a medical review.

Table 33. Guidelines for reviewing literature.(Oxman & Guyatt 1988)

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Medical reviews may list the findings of different studies or integrate some data qualitatively but, more often, results are difficult to compare due to the variability in the populations sampled. It has been noted that in the same way that flawed methods in a study of diagnosis or therapy may lead to invalid results, so an unscientific review may also come to incorrect conclusions (Oxman and Guyatt, 1988).

The systematic review gained favour in the medical profession in the early 1990s as a way of minimising bias and random errors such as those occurring with a traditional review. The terms systematic review and meta-analysis are often used synonymously although "meta-analysis", originally used by Glass in psychological literature in 1976 (Goodman, 1991), is specifically defined as *"the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating the findings"* (Dickersin et al., 1994). A systematic review may include meta-analysis if results from studies are combined. At times the quantitative synthesis of data is not possible in which case the review does not contain meta-analysis.

The purpose of the systematic review is more narrowly focused compared with a traditional review, often examining a single clinical question and having a logical framework. The review has a predetermined protocol so that search methods, quality assessment, outcome measurement and data analysis are decided upon before the trials are identified. The set of studies should include all appropriate trials in the field and the literature is combed systematically so that no paper is missed. The quality of a study to be included is assessed using pre-set criteria so that the quality assessment is identical for all trials. The quality assessment score may be used in reviews that have a large number of trials to include so that a minimum level for quality must be reached before a trial is included into the review. Assessment of trial quality is controversial. Assessment of quality is dependant on the information presented in the trial publication and authors may not have described the finer details of their methods.

The protocol details the purpose and design of the study and establishes the procedures to be used prospectively. The essential elements for a protocol are given in the Cochrane Handbook (Clarke and Oxman, 2000) and are summarised below:

1. The review question

The research question allows for the focus of the review to be set and determines the criteria for inclusion of the trials. With very specific questions, the populations, interventions and outcome measures may be set in the question. For broader reviews, a number of interventions may be considered together.

2. Study designs for inclusion

Treatment effects are most often assessed using randomised-controlled trials. Systematic reviews with other questions such as aetiologies, prevalence rates, diagnostic techniques may use other study designs. The design to be used is stated in the protocol.

3. The search strategy

In order to report comprehensively on current knowledge, the systematic review must include all the appropriate studies undertaken on a specific topic. To identify all the published and unpublished data, a detailed search strategy is required. The search terms to be used and MeSH for electronic databases should be described, the journals to be scrutinised through hand-searching should be listed, the intentions regarding articles published in languages other than English and contacting authors needs to be stated.

4. Quality assessment and data extraction

A quality assessment form must be designed prospectively and intentions regarding the number of assessors and blinding of assessors should be stated as well as the method of arbitration in the event of disagreement. The outcomes to be measured should also be chosen prospectively and the intention to use two assessors to extract data should be stated if it is to be undertaken. The use of two reviewers for quality assessment and data extraction reduces error and minimises reviewer bias.

5. Data synthesis

A statement of the intended methods to be used to produce results should be given in the protocol.

Although a systematic review attempts to reduce some of the bias involved in a traditional review by having a protocol with set inclusion criteria and a systematic method of searching the literature, there are forms of bias that cannot be avoided. As with the traditional review, when published trials form the greater part of a systematic review, the review will be subject to "publication bias". This bias results from the trend to publish and present studies that show significant differences in favour of the treatment whereas many non-significant trials go unreported. The main source of this bias is from the trialists themselves, who tend not to submit studies with unfavourable results. Journal editors have shown less bias to publishing significant versus non-significant studies (Easterbrook et al., 1991). It has also been found that the desire to produce positive results may also lead author to dredge the data for favourable results or the trial may have a short follow-up due to the pressure to publish positive results as soon as possible (Stewart and Parmer, 1993). Easterbrook *et al* (1991) found that the publication of research that only has positive outcomes tended to overestimate the treatment effect or risk factors in systematic reviews. More important than the effect on the results of a review, unreported trials may lead other groups repeating the same study and lead to patients volunteering for trials and receiving treatments that do not to work because the knowledge is not in the public domain.

For systematic reviews on treatment effectiveness, the randomised-controlled trial (RCT) is considered the gold standard for trial inclusion. Randomised controlled trials are defined as clinical experiments in which the patients receive the treatment through a method of distribution that results in the allocation being randomly distributed (Dickersin et al., 1994). A control group is used to provide a reference measure against which treatment outcome can be compared. The first RCT in medicine was undertaken in 1948 when streptomycin was tested for efficacy in TB. The allocation of the treatment or control (bed rest) was undertaken with the use of random numbers concealed in sealed envelopes. Other methods of allocation used in RCTs include the use of the patient's hospital number or their date of birth. Methods such as these may result in patterns that are not the result of chance alone and are called "quasi-randomisation". Having stated that RCTs are the gold standard for use in systematic reviews, it should be stated that this is not the case for all reviews. The Cochrane Collaboration has attracted criticism for including only RCTs despite some findings that the results of meta-analysis of non-randomised trials compared to randomised trials showed no overall difference (Chalmers, 1991a; Black, 1996). The NHS Centre for Reviews and Dissemination encourages the inclusion of non-randomised trials especially in the absence of RCTs.

In a good RCT, the use of sealed envelopes when allocating treatment is undertaken in an attempt to reduce further bias related to either the patient or the assessor knowing which treatment is to received. It is essential that the patient and those recruiting the patients are unaware of the treatment to be assigned. A central randomisation centre is required and some method of concealing the assigned treatment is adhered to. Blinding the patient or the treatment provider to the allocation group after allocation is an ideal but it is frequently not possible to undertake. However it will not affect the selection bias. More frequently, blinding the outcome assessors to the treatment allocation is possible and should be attempted in a good quality trial.

A further form of bias often seen is "attrition bias". This explains some differences between the comparison groups due to the numbers of patients lost to the study. Patients should be analysed by their initial allocation even if they changed treatment at some stage and data from patients withdrawing from the study included whenever possible. The results at follow up should be treated with caution if the intention to treat data are not included or losses are not described (Clarke and Oxman, 2000).

Both the method of randomisation and the concealment of allocation are considered the most important areas when grading the quality of the trial, however the other types of bias need consideration. Quality assessment of individual trials is used to recognise the bias involved, enable comparison between studies and guide interpretation of the studies (Clarke and Oxman, 2000). The quality of a trial in a systematic review is often graded using a checklist so that each trial is subjected to exactly the same scrutiny. The Consolidated Standards of Reporting of Trials (CONSORT) provides a checklist of 21 items for the evaluation of internal and external validity of RCTs (Begg et al., 1996). The checklist was developed after a group of journal editors, clinical epidemiologists and statisticians met in 1995 to formulate reporting guidelines with the aim to provide standards and improve reporting of RCTs (Moher et al., 2001). The checklist asks questions concerning areas such as the use of inclusion / exclusion criteria, appropriateness of outcome measures, method of treatment allocation, concealment of treatments from patients and assessors, length of follow-up and intention to treat analysis (Glaszoiu et al., 2001). Such checks are used when assessing the quality of RCTs for reviews either in the original CONSORT format or are adapted to suit the individual review.

It has been suggested that the quality assessment should be undertaken by more than one reviewer and that blinding the reviewers to the authors, institutions, journal and results of the study produces more consistent scores. However, the evidence to support this is not complete (Clarke and Oxman, 2000). The assessment of quality is also limited by the reporting of the trial. It is not possible to assume that because it was not reported that something was not done. Further to this, if the authors of some trials are contacted for further results, information on quality may be ascertained at the same time. This may cause some trials to appear to have better quality than others when the differences were in the level of reporting rather than in the trials themselves. The Cochrane Collaboration recommends that reviewers should not put undue reliance on detailed quality assessment (Clarke and Oxman, 2000).

When analysing the results of a review, meta-analysis can provide more information than the systematic review. Once differences between patients, protocols and interventions are identified, trials that are comparable may be combined and statistical tests applied in meta-analysis. By having a larger overall trial size through combining the studies, the overall power of the study is increased and small effects or subgroup effects may be identified that would not have shown up in an individual, smaller trial (Goodman, 1991; Dickersin et al., 1994). However, the results of a meta-analysis do have limitations. According to Goodman, systematic reviews / meta-analyses "*often purport to provide definitive answers to a clinical question*". The author advises that such an idea should be viewed with caution. A systematic review may not aid the decision on how to treat an individual since the review may include trials that involve many populations different to that person. A single clinical trial on patients similar to the individual would be more useful (Thompson and Pocock, 1991).

Like any other study, there is still a question as to how repeatable and accurate the results of a systematic review are. In determining the repeatability, it has been found that the interpretation of the results differs between authors (Chalmers, 1991a). Doubt has also been placed upon the correctness of the statistical tests when combining the results of many studies. For example, trials may show heterogeneity in that they involve patients from different populations, different ages, or be in different stages of the disease process. The studies may use different diagnostic techniques or have different outcome scales. Combining the data from such trials may be inappropriate and tests for heterogeneity are not very sensitive since they are based upon the assumption that the sampling of results is random. In most cases the treatment groups are compared for heterogeneity when the control groups show the influence of any differences more readily. Chalmers (1991b) however argues that meta-analysis should not be mistrusted on the basis of the statistics but should be trusted for its superiority over a traditional review. He described how a meta-analysis of four small trials predicted the results of a larger trial. Such predictability of a review is desirable and adds to the trustworthiness of the research method.

The systematic review for treatments of hallux abductovalgus was undertaken using the methods advised by the Cochrane Collaboration. This organisation was named after Archie Cochrane (1909-1988), an epidemiologist interested in effective care. Although a supporter of the NHS, Cochrane was critical of the health service for not looking at whether treatments were effective or ineffective. Although the individual clinician may well have formed a view on how effective a treatment was, based upon reading the available literature and personal experience, the specialities were not generally organised or leading best practice. In 1992 the first Cochrane Centre was opened. This aimed to keep a registry of all trials so that future research could be planned with the knowledge of what studies had already been undertaken. In 1993, the organisation became international and has built up to include 50 review groups to cover the treatment of different diseases or health problems. The Cochrane Library is the central database for systematic reviews undertaken through the Cochrane Collaboration, including completed and extant reviews so that duplication can be avoided.

6.2 A systematic review in hallux abductovalgus

6.21 Background

Over the past century, around 100 surgical procedures for the treatment of HAV deformity have been described (Mann and Coughlin, 1999). However, very few of these have been evaluated through the use of randomised controlled trials. Fewer conservative treatments have been developed and, again, these have rarely been evaluated. Conservative treatments may be undertaken when the deformity first presents and are aimed at preventing deterioration of the deformity rather than correction. Such treatments include the use of orthoses to control subtalar joint pronation and improve 1st ray function (Tax, 1980) and the use of night splints to counteract the tightening of the lateral soft tissues (Groiso, 1992). Toe separators and exercises have also been used (Bek and Kurklu, 2002). Conservative treatments are often used in children. In established HAV deformity, conservative treatments may be of little use in correcting the deformity but may be of benefit in reducing pain. The limited availability of conservative therapies may reflect the lack of knowledge regarding the cause of HAV and thus the inability of the therapist to develop a suitable treatment regimen.

The surgical options are numerous. Surgical treatments involve either bony or soft tissue correction or a combination of these. The simplest procedure is to shave off the bony prominence on the metatarsal that rubs against the shoe (eg. exostectomy). More complex procedures involve the removal of the medial prominence and the base of the proximal phalanx of the great toe (eg. Keller's arthroplasty) leaving a flexible joint or removal of both joint surfaces followed by the implantation of a false joint. The joint may be fused so movement cannot take place between the bones (ie. arthrodesis). Other operations aim to realign the 1st metatarsal head under the proximal phalanx. This is undertaken by cutting the metatarsal or creating a wedge at some point along the length of the bone so that the distal portion of the metatarsal can be moved into a new position (ie. metatarsal osteotomy). These procedures can be done on any part of the metatarsal and are often undertaken in conjunction with soft tissue procedures to alter the action of surrounding ligaments and muscles. The procedures are frequently named after the surgeon developing the operation, for example Mitchell's or Wilson osteotomy, or describe the shape or placement of the cut in the bone, for example, chevron or crescentic osteotomy. Finally, the proximal phalanx of the hallux may be operated on to change the alignment, for example, Akin osteotomy. Many of the 150 operations described in the literature are simple variations on these principle procedures.

Surgery is the only method of achieving correction. Adults typically present for treatment of HAV when the condition becomes painful or acceptable footwear becomes difficult to find. Despite HAV being reported in some unshod populations, the condition only becomes painful and treatment sought in shod populations (Kusumoto et al., 1998). The continual development of new surgical technique perhaps suggests that the present operations are not wholly successful or the lack of any evidence regarding effectiveness encourages new procedures to be attempted.

Given the prevalence of hallux valgus (chapter 1) and the personal and economic costs of treatment and the variety of treatments available, a systematic review of the effects of treatment intervention for the deformity was warranted. Consideration of the treatment types with respect to the etiology of the condition was also made.

6.22 Aim

The aim of the systematic review was to review the success of the treatment interventions available. For this review, it was decided that the evaluation of treatment should be primarily based on reduction of deformity, improvement in pain, improvement in function and patient satisfaction.

The treatments identified through randomised controlled trials was compared to the current knowledge on the etiology of the deformity, with particular emphasis on the increased prevalence in the female foot, to investigate whether the treatment modalities address underlying etiological factors.

6.23 Review Objectives

The initial objectives were:

1. To identify trials which evaluated the treatments used in the correction of hallux valgus.

2. To compare outcomes in order to establish the effectiveness of the treatments when they have been compared with untreated control groups or with other treatment techniques.

3. To explore whether there was an optimal treatment for hallux valgus.

Interventions were categorised into surgical and conservative treatments, and the following comparisons made:

a. conservative versus no treatment

b. conservative versus conservative

c. surgical versus conservative

d. surgical versus no treatment

e. other operative procedures versus Keller's arthroplasty

f. other treatments (including no treatment) versus chevron (and chevron-type) osteotomy

g. surgeon's adaptation versus original operation

h. new methods of fixation versus traditional method

i. comparison of post-operative rehabilitation regimens

6.24 Methods

The title was registered with the Cochrane Collaboration Musculoskeletal Injuries Group. This group provided support during the review process, gave advice to improve the quality of the review and provided guidelines for publication of the report in a format compatible with the Cochrane Library so that the review could be disseminated once complete.

Types of studies:

Any randomised controlled trial or quasi-randomised controlled trial (methods allocating participants to a treatment which is not strictly random eg. date of birth, hospital record number) on the treatment of hallux valgus was considered for inclusion.

Types of participants:

All patients presenting for treatment of hallux valgus were included. No specific definition of hallux abductovalgus was sought. The characteristics of patients included in the trials were noted with emphasis on recording age group, activities (ie. athletes or dancers), health status (arthropathies or neurological disease) and gender. All age groups and both genders were included.

Types or interventions:

For the purpose of the review, all treatments that potentially had an influence on joint position, joint function or the treatment of chronic pain were considered. Trials undertaken in gait laboratories where no specific treatment was investigated were excluded as were trials of analgesics used in the short term for post-operative pain.

The treatment interventions considered included:

i. Conservative:

Splinting – corrective devices strapped to the toe worn during day or at night

Orthoses – insoles designed to alter the function or pressure distribution of the foot

Exercises – to strengthen extrinsic or intrinsic muscles

ii. Surgical:

Fusion – an arthrodesis that permanently fuses the first metatarsophalangeal joint

Excision arthroplasty - whereby part of the joint is removed but the joint is left mobile (eg. Keller's)

Replacement arthroplasty – whereby all the joint is removed and a false joint is implanted

Osteotomy – a wedge of bone or a cut is made across the metatarsal in order to realign the bone (eg. Wilson, chevron). The metatarsal may be operated on distally or proximally and may involve additional procedures to the soft tissue structures surrounding the joint.

Soft tissue procedures – whereby the position or function of the surrounding ligaments and tendons are altered.

Fixation techniques – the use of screws, pins or sutures to hold the cut bone ends together.

Types of outcome measures:

Outcomes sought included both "objective" and "subjective" outcomes.

"Objective" data describe the information measured by the practitioner directly from the patient and included:

a) hallux abductus (HV) angle (the final, actual angle following operation was used rather than degrees of improvement in angle). The angle was measured radiographically or clinically with a goniometer.

b) 1st intermetatarsal (IM) angle (the final, actual angle following operation was used rather than degrees of improvement in angle). The angle was measured radiographically.

c) range of motion measurements (ROM) of the first metatarsophalangeal joint (the final, total range of both dorsiflexion and plantarflexion was used to calculate the range).

d) complications (the number of complications was used, and included complications such as infection, re-operation, non-union, avascular necrosis) .

"Subjective" outcome measures describe data reported by the patient and included:

e) global assessment (the number of patients reporting the condition as being the same or worse than before treatment).

f) functional assessment (the hallux-metatarsophalangeal AOFAS (American Orthopaedic Foot and Ankle Society) score (0-100) at final follow-up).

g) post-operative pain levels (the number of participants remaining in pain, or the pain level measured on a visual analogue scale (0-100) was used).

h) post-operative satisfaction levels (this included general satisfaction as well as satisfaction with appearance. Numbers of participants dissatisfied, or the level of dissatisfaction on a visual analogue scale (0-100) at the end of the trial was used).

i) footwear problems (the number of participants requiring specialist or extra-width footwear, or reported as having difficulty with footwear).

j) limitation in walking (the number of participants described as having problems with mobility).

k) quality of life index (the score at final follow-up on a health-related index).

The results of outcomes used in the review were those given for final follow-up, regardless of the length of the follow-up, even if interim data were available.

Search Strategy

A search was made of the Cochrane Library (2003/1) which holds the most comprehensive database for systematic reviews. It also contains the Cochrane Musculoskeletal Injuries Group trials register and the Cochrane Controlled Trials Register for the initial search for trials. MEDLINE (January 1966 to March 2003) was searched being the electronic database containing the largest collection of medical journals. EMBASE, CINAHL and AMED databases were searched for further trials related to other health professions such as nursing and the professional allied to health.

Since many podiatry journals are not held on electronic databases, the following journals were handsearched: the British Journal of Podiatric Medicine (formally The Chiropodist) (1957-March 2003); The Foot (1994-March 2003); Foot and Ankle

International (1980-March 2003); The Journal of the American Podiatric Medical Association (1967-March 2003); Journal of Foot & Ankle Surgery (formally Journal of Foot Surgery)(1980-March 2003), Foot and Ankle Surgery (Journal of the European Foot and Ankle Society) (2000 - 2002) and The Australian Journal of Podiatry (1990-November 2002).

No language restrictions were applied and foreign language paper was translated if the abstract suggested the trial should be included.

The electronic search was carried out for MEDLINE (SilverPlatter), using the following specific search terms combined with the optimal trial strategy described by Clarke (Clarke and Oxman, 2003):

1. "HALLUX VALGUS" / all subheadings
2. "METATARSOPHALANGEAL JOINT" / all subheadings
3. bunion*
4. (great near toe*)
5. (deform* or valgus or deviat*)
6. (#4 and #5)
7. ((hallux near abduct*) or (hallux near valgus))
8. (#1 or #2 or #3 or #6 or #7)

(A description of the full search strategy can be found in Appendix VIII)

Electronic searches of EMBASE (1980 - January 2003), CINAHL (1982 - Oct 1998) and AMED (1983 - Oct 1998) was carried out using broad search terms only.

The reference sections of identified trials were checked for further appropriate studies. Lead authors were contacted if additional information was required for any study.

Quality Assessment

An assessment based upon a design used by the Cochrane Musculoskeletal Injuries group was used to assess quality. Each trial was assessed on 12 different methodological criteria. A maximum of 2 points were available for each criterion giving a maximum overall score of 18 points (see table 34). Each trial was assessed by two reviewers. One reviewer was blinded to the author and institution producing the trial. When the assessment was complete, the scores were discussed by the reviewers and disagreements between scores were resolved. All foreign language articles were translated prior to quality assessment.

Data extraction

Data were collected using a pre-derived data extraction form. The data were extracted by two reviewers, one of whom was masked to the author and institution of publication in an attempt to reduce bias. A proforma was used for data extraction (see table 35.

Table 34. Systematic review: Treatment of hallux valgus - Quality Assessment Tool

Study ID: .... Raters initials: .... Date: ....

		Score	Query
A	Was the assigned treatment adequately concealed prior to allocation? 2 = method did not allow disclosure of assignment 1 = small but possible chance of disclosure of assignment or unclear 0 = disclosure likely: quasi-randomised or open list / table		
B	Were the outcomes of patients who withdrew from the study described and included in the analysis (intention to treat)? 2 = intention to treat analysis based on or carried out on all cases randomised 1 = states number and reasons for withdraws but intention to treat analysis not possible 0 = not mentioned or states numbers of withdraws only		
C	Were the outcome assessors blind to the treatment status? 2 = effective action taken to blind assessors 1 = small or moderate chance of assessors being unblinded 0 = not mentioned or blinding not possible		
D	Were the subjects blind to the assignment status after allocation? 2 = effective action taken to blind subjects 1 = small or moderate chance of unblinding subjects 0 = not possible or not mentioned or possible but not done		
E	Were the treatment and control groups comparable at entry? 2 = good comparability of groups or confounding adjusted for in analysis 1 = confounding small; mentioned but not adjusted for 0 = large potential for confounding or not discussed		
F	Were the care programmes, other that trial options, identical? 2 = care plans identical 1 = clear but trivial differences 0 = not mentioned or clear and important differences in care programmes		
G	Were the inclusion and exclusion criteria clearly defined? 2 = clearly 1 = adequately defined 0 = not defined		
H	Were the interventions clearly defined? 2 = clearly defined interventions are applied with a standardised protocol 1 = clearly defined interventions are applied but the application protocol is not standardised 0 = intervention and / or application protocol is poorly or not defined		
I	Were the outcome measures that were used clearly defined? 2 = clearly defined 1 = inadequately defined 0 = not defined		

TOTAL /18

Table 35. Data Extraction Form

Author: ID

Title:

Aim:

Length of follow up:

Characteristics: Outcomes included:

Outcome		**absorbable (treatment)**	**Suture (control)**
Numbers in trial (Please state whether data are numbers of Feet or Patients?)			
HV angle (the final, actual angle after treatment – not improvement in treatment)	mean		
	SD		
	95% CI		
	Other (state)		
1st IM angle (the final, actual angle after treatment – not improvement in treatment)	mean		
	SD		
	95% CI		
	other		
Range of motion (the final range of dorsiflexion plus plantarflexion)	mean		
	SD		
	95% CI		
	other		
Number of Complications	No.		
Post treatment pain levels – numbers in pain / no pain at end of study	Number with pain		
	Number without pain		
Post treatment satisfaction levels – numbers satisfied / dissatisfied at end of study	Number satisfied		
	Number dissatisfied		
Footwear problems (numbers requiring specialist or extra depth footwear) at end of study	Number with problems		
	Number without problems		
Limitation walking (number of patients reported as having difficulty with mobility) at end of study	Number with problems		
	Number without problems		

The trials included were assigned to one of six categories, based on the following comparisons:

a. conservative treatment versus no treatment

b. conservative treatment versus conservative treatment

c. surgical treatment versus conservative treatment

d. surgical treatment versus no treatment

e. other operative procedures versus Keller's arthroplasty

f. other treatments (including no treatment) versus chevron (and chevron-type) osteotomy

g. surgeon's adaptation versus original operation

h. new methods of fixation versus traditional method

i. comparison of post-operative rehabilitation regimens

6.25 Data Analysis

◊ Continuous data were analysed using mean differences and 95% confidence intervals to test for differences between the treatment groups

◊ Dichotomous data were analysed using odds ratios to measure differences between the treatment groups.

◊ Because of the heterogeneity between the interventions under comparison, data were not pooled.

◊ Several of the trials included were randomised by patient but presented results in terms of numbers of feet. Such analyses may be misleading due to the correlation between feet of the same patient. As a conservative analysis, numbers within each trial were reduced to a denominator of the number of patients. This corresponds to an assumption of patients having symmetrical and equally deformed feet with an identical response to treatment. When a trial failed to state the number of patients (PE) with a particular outcome and instead presented the number of feet (FE) with that outcome, the numbers of patients with that outcome were derived by multiplying the number of feet by the ratio of the total number of patients (PO) divided by the total number of feet (FO) in each group (PE = FE x PO / FO), and rounded appropriately.

◊ Many trials considered patient satisfaction as an outcome but failed to record the numbers of patients dissatisfied at the start of the trial. It was therefore assumed that all patients were dissatisfied at the start of the trial.

◊ When standard deviations were not reported, the largest standard deviation available across all trials was used for analysis purposes, providing it seemed a reasonable figure given the patient numbers and means of the individual trial. The values for the standard deviations, and their sources, which were used in the absence of standard deviations in individual trials are given below:

Imputed SD:

for HV angle = 12.40 degrees (O'Doherty et al., 1990)

for IM angle = 5.40 degrees (Resch et al., 1993)

for Range of Motion = 11.00 degrees (Klosok et al., 1993)

for Functional Assessment (AOFAS score) = 13 degrees (Torkki et al., 2001)

6.26 Results

Sources of the identified randomised controlled trials

A total of 19 trials published as full journal articles were included in the review. Two further trials were reported in abstract form only (Joukainen et al., 1998; Partio et al., 1998) but had insufficient data to include them in the analysis. The authors were contacted but failed to reply to the request for further data. A further 11 trials were excluded after the full journal article was obtained

.

The specific MEDLINE search from 1966 to March 2003 produced 32 potential trials of which 21 were prospective randomised controlled trials (RCTs), including a Brazilian study (Ruaro et al., 2000) that was obtained through a British Library world search and was translated prior to inclusion. One further study (Bek and Kurklu, 2002) was published in Turkish with an English abstract. The abstract claimed that the trial was randomised and so the full article was translated. There was little information on the method of randomisation in the full paper and suspicions were raised when each treatment group had equal numbers of patients. Contact was made with the author who reported the trial was not randomised and so the trial was excluded. Another trial was not included but may be relevant to the review (Christenson and Jones, 1991). It was unclear from the article whether the study was randomised. The authors were contacted but no reply was received. A conference abstract (Watson et al., 1996) for fixation of first metatarsophalangeal joint arthrodesis was excluded as it did not state whether HAV was the underlying pathology.

The EMBASE, CINAHL and AMED searches produced no further RCTs.

The Cochrane Central Register of Controlled Trials listed several trials which were covered by MEDLINE. Of these, one (Khan, 1996), was rejected since it did not appear to be an RCT and although the author was written to regarding this, no satisfactory response was received. A second trial (Budiman-Mak et al., 1995) was rejected as it was a preventative study and no participants had hallux abductovalgus at the start of the trial. Another trial was published in German (Trnka et al., 1997) but was found not to be a prospective study once the method section was translated.

One conference abstract was found in the British Journal of Podiatry through hand-searching. The unpublished RCT was from an MSc thesis. The thesis was reviewed and relevant data extracted.

The 21 trials included involved 1213 patients. The participants were predominantly female (91%) and the age range of the participants was 9-81 years. Except for one trial (Kilmartin et al., 1994b), which focused on juvenile HAV in 9 to 10 year old children, all other trials tended to involve adult populations. Most trials did not define the underlying etiology or associated pathology. Four trials specifically excluded patients with rheumatoid arthritis (Basile et al., 2000; Prior et al., 1997; Juriansz, 1996; Torkki et al., 2001) and another (Kilmartin et al., 1994) excluded patients with neurological or systemic connective tissue disease. Klosok (1993) included seven participants with rheumatoid arthritis and two trials (O'Doherty et al., 1990; Sherman et al., 1984) included participants with hallux rigidus as well as hallux valgus.

Three trials considered conservative therapies.

Conservative treatment versus no treatment:

Three trials involving 288 participants compared conservative treatment with no treatment. Night splints were used by Juriansz (1996) which involved 28 people with hallux valgus aged from 10 to 77 years. The group consisted of 27 females and one male. Subjects with rheumatoid and osteoarthritis were excluded and no specific etiologies of the HAV were given. Functional orthoses were used by Kilmartin *et al* (1994) which involved 122 school children, 106 girls and 16 boys. The orthoses were designed to control excessive pronation so it may be assumed that the underlying etiology being addressed was excessive pronation. Torkki (2001) compared 69 adult patients (mean age 49 years) prescribed functional orthoses with 69 adult participants receiving no treatment. There were 194 females and 17 males. The functional orthoses were made to the individual patient requirements. Although not stated, these devices aim to hold the foot in it's best functional position, preventing mechanical malalignment. It was not stated whether all or any of the patients had an underlying biomechanical problem treatable with orthoses.

Conservative treatment versus conservative treatment

No trial was found for this comparison.

Fourteen trials considered surgical treatment.

Surgical treatment versus conservative treatment:

Torkki 2001 compared 71 participants (mean age 48 years) receiving a chevron osteotomy with 69 patients being treated with functional orthoses. The chevron osteotomy reduces the 1st metatarsus primus varus position and so this appeared to be etiology being addressed. The mean intermetatarsal angle prior to surgery was 10-11 degrees.

Surgical treatment versus no treatment:

Torkki (2001) also compared 71 adult participants undertaking a chevron osteotomy with 69 participants receiving no treatment.

Other operative procedures versus Keller's arthroplasty:

Two trials involving 133 participants compared Keller's arthroplasty with other operations. Keller's was compared with arthrodesis by O'Doherty *et al* (1990) in a study involving 100 participants aged from 45 to 81 years old. There were 70 females and 11 males included at follow-up. The Keller's procedure is used on older patients who may have osteoarthritic change in the joint and corrects the deviation of the hallux. The arthrodesis is usually used for painful arthritic joints. No specific etiologies of the HAV deformity were given. Turnbull and Grange (1986) studied 34 participants aged from 32 to 79 years old in a trial of Keller's arthroplasty versus distal osteotomy. There were 22 females and 7 males. No specific etiologies were discussed. The distal osteotomy corrects an increased intermetatarsal angle such as occurs with metatarsus primus varus. The pre-operative mean IM angle was between 13 and 16 degrees.

Other operative procedures versus chevron (and chevron-type) osteotomy:

Six trials involving 256 participants, aged between 16 and 78 years old, compared chevron osteotomy with other operations. The trials in this group were considered in two groupings: those involving a distal chevron procedure and those using a proximal chevron procedure.

Klosok *et al* (1993) compared the chevron with the Wilson osteotomy in 51 participants. The study included 44 females and 7 males. Again the procedures used were addressing the metatarsus primus varus deformity. Resch *et al* (1991) compared the chevron to the proximal osteotomy in 79 participants. There were 61 females and 7 males. The etiologies involved were not given but the operations aimed to correct the high IM angle. Basile compared 14 patients undergoing a chevron-Akin osteotomy with 18 participants undergoing an Akin osteotomy combined with distal soft tissue reconstruction (Basile et al., 2000). There were 29 females and 3 males. The Akin osteotomy corrects abduction occurring from the proximal phalanx. One study, reported in abstract form only (Partio et al., 1998), compared the chevron osteotomy to a proximal osteotomy in 47 patients (44 females, 3 males) when both types of osteotomy were fixed with absorbable rods.

Two trials compared proximal osteotomies to proximal chevron osteotomoies. Easley *et al* (1996) compared the proximal chevron osteotomy with the proximal crescentic osteotomy in 75 patients. The study included 63 females and 3 males. Both operations aim to correct the metatarsus primus varus deformity and the pre-operative IM angle was between 15 and 16 degrees. Ruaro *et al* (2000) compared the proximal osteotomy to the proximal chevron osteotomy in 24 feet (19 patients). All patients were female.

Surgeon's adaptation versus original operation:

Three trials involving 157 people with hallux valgus compared a surgeon's adaptation with the original operation. Capasso *et al* (1994) involved 35 participants aged from 55 to 76 years and compared operations with and without an additional tendon transfer. There were 34 females and one male in the study. The operation involved a Keller's type procedure followed by a tendon transfer of the extensor hallux brevis muscle to improve the abductory force on the metatarsal head preventing the development of metatarsus primus varus. The etiologies of the deformity were not given for the group of patients. Resch *et al* (1994) undertook a similar study comparing the transfer of a different tendon in 87 participants aged from 15 to 74 years old. There were 83 female patients and 1 male patient. The chevron osteotomy was used to address the metatarsus primus varus deformity with or without an additional adductor tendon tenotomy to improve muscle pull. Sherman *et al* (1984) involved 35 participants aged from 44 to 77 years old (all patients were female) in a study comparing distraction of the joint following a Keller's arthroplasty, with no distraction. Etiological factors were not discussed.

New methods of fixation versus traditional method:

Two studies involving 58 people with hallux valgus, aged between 16 and 68 years old, compared methods of fixation of bone ends following Mitchell's osteotomy. Calder *et al* (1999) compared the use of screw fixation to the originally described suture fixation in 30 participants, 24 females and 6 males. Prior *et al* (1997) compared the use of Orthosorb Absorbable Pins to the traditional method (sutures or K wire fixation) in 28 participants, 25 females and 3 males. One study published in abstract form also compared methods of fixation. Joukainen *et al* (1998) compared 13 participants (mean age 53 years, all female) in a study of two types of self-reinforced poly-L-lactide screws. The Mitchell's osteotomy also addresses an underlying metatarsus primus varus deformity. No specific etiological factors were discussed in this study which is generally acceptable given that the studies were considering the method of fixation rather than the appropriateness of the operation type, however conditions such as rheumatoid arthritis may have an associated osteopenia which can affect fixation.

Three trials compared post-operative care.

Comparisons of post-operative treatment regimens:

Four trials involving 189 people with hallux valgus compared a different post-operative regimen with the standard treatment. Connor *et al* (1995) looked at continuous passive motion after surgery in a trial of 39 participants, 36 females and 3 males. Lampe *et al* (1991) studied 56 participants (40 females and 16 males) in a trial on early versus late weightbearing following surgery. Meek and Anderson (1998) studied 40 participants in a trial comparing the use of crepe bandage applied post-operatively to the traditional method of post-operative plaster cast slippers following first metatarsophalangeal joint fusion. The sex of the participants was not stated. The study was repeated a year later with 54 participants in a trial comparing the crepe bandage to plaster cast slippers following a Wilson's osteotomy. Again, the sex of the subjects was not given.

The quality of the methods used in the trials included

The method quality scores for the 21 trials included are shown below. Full details of the scores can be found in Appendix IX. The maximum possible score per trial was

18 and each trial was graded for allocation concealment (A- concealed assignment, B- possible disclosure/unclear, C- disclosure likely).

Brief reminder of scoring schemes:

A = concealed assignment

B = withdrawals described, intention to treat analysis

C = assessors blinded

D = subjects blinded

E = groups comparable at entry

F = identical care programs

G = inclusions/exclusions defined

H = interventions defined

I = outcomes defined

Conservative treatment versus no treatment:

Juriansz 1996 scored 7/18 and had concealment allocation B

Kilmartin 1994 scored 8/18 and had concealment allocation B

Surgical treatment versus no treatment:

Surgical treatment versus conservative treatment:

Torkki 2001scored 13/18 and had concealment allocation A

Other operative procedure versus Keller's arthroplasty:

O'Doherty 1990 scored 4/18 and had allocation concealment C

Turnbull 1986 scored 3/18 and had allocation concealment C

Other operative procedure versus chevron (and chevron-type) osteotomy:

Klosok 1993 scored 4/18 and had allocation concealment B

Resch 1993 scored 6/18 and had allocation concealment B

Basile 2000 scored 10/18 and had allocation concealment C

Partio 1998 scored 4/18 and had allocation concealment B

Ruaro 2000 scored 9/18 and had allocation concealment B

Easley 1996 scored 9/18 and had allocation concealment B

Surgeon's adaptation versus original operation:

Capasso 1994 scored 6/18 and had allocation concealment B

Resch 1994 scored 7/18 and had allocation concealment A

Sherman 1984 scored 9/18 and had allocation concealment B

New method of fixation versus traditional method:

Calder 1999 scored 8/18 and had allocation concealment A

Prior 1997 scored 11/18 and had allocation concealment B

Joukainen 1998 scored 1/18 and had allocation concealment B

Comparisons of post-operative rehabilitation regimens:

Connor 1995 scored 7/18 and had allocation concealment B

Lampe 1991scored 8/18 and had allocation concealment B

Meek 1999 and Meek 1998 both scored 8/18 and had allocation concealment B

In only three of the trials was allocation clearly concealed. Torkki (2001) stated closed envelopes were used with an independent assessor involved in opening the envelope. Resch *et al* (1994) and Calder *et al* (1999) mentioned the use of closed envelopes but did not give details on actual concealment. Klosok *et al* (1993) used computer-generated random number tables but did not mention the method of concealment. The method of randomisation was not stated in ten trials. Four trials (O'Doherty 1990; Turnbull 1986; Basile 2000; Ruaro 2000) used quasi-randomisation methods based on date of birth, hospital number or alternating the treatment. Many of the trials randomised treatments by patient but analysed results by feet (Easley 1996; Juriansz 1996; Klosok 1993; Lampe 1991; O'Doherty 1990; Resch 1993; Resch 1994; Sherman 1984; Turnbull 1986; Prior 1997). In the study by Basile *et al* (2000), it was unclear whether the authors had randomised by participants or by feet, but outcomes were described in numbers of participants. Meek 1999 replied to a request for further information and confirmed that they randomised their treatments by numbers of feet and analysed by numbers of feet.

Although most trials had reasonable scores regarding the definition and usefulness of outcome measurements (item I), the trials were generally very poor in quality regarding intention to treat analysis (item B) and blinding procedures (items C, D) although this may not have been possible in several of the studies.

Outcome measurements

CONSERVATIVE TREATMENT VERSUS NO TREATMENT

Three trials of moderate-good method quality reported conservative treatments:

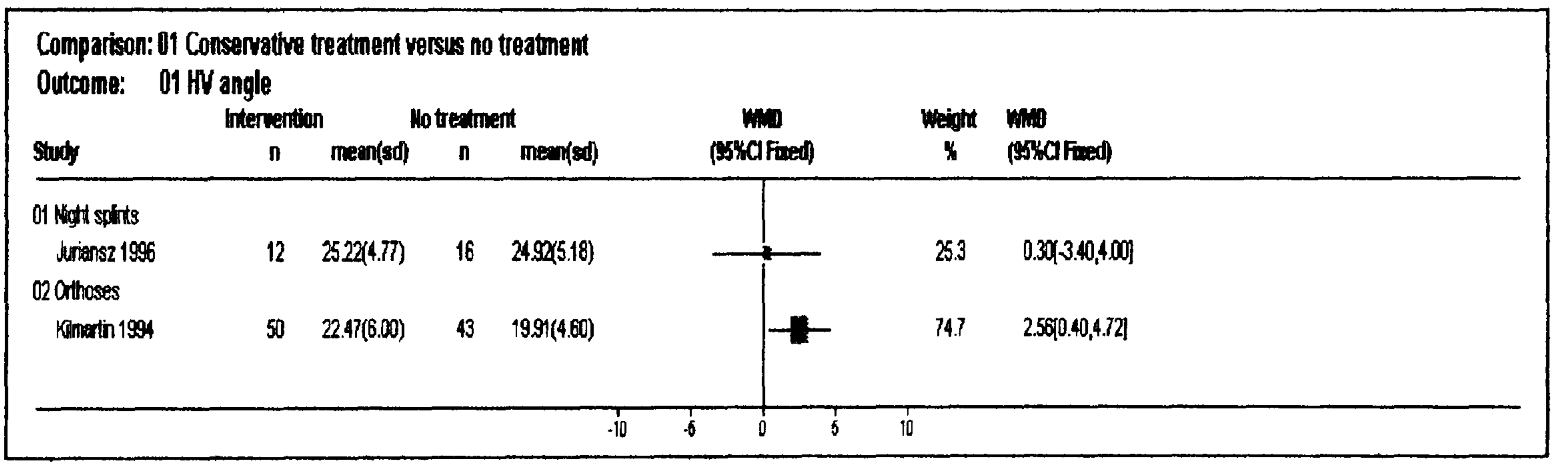
Night splints versus no treatment (Juriansz, 1996)

Foot orthoses versus no treatment (Kilmartin et al., 1994; Torkki et al., 2001)

a) Hallux valgus (HV) angle

Both Juriansz 1996 and Kilmartin 1994 reported this outcome but only Kilmartin 1994 showed evidence of a difference in HV angle, in favour of the control group (Mean Difference (MD) = 2.56 degrees, 95% CI = 0.40 to 4.72 degrees). The HV angle in both the treatment and control groups deteriorated; the deterioration was greater in the group treated with orthoses (figure 83).

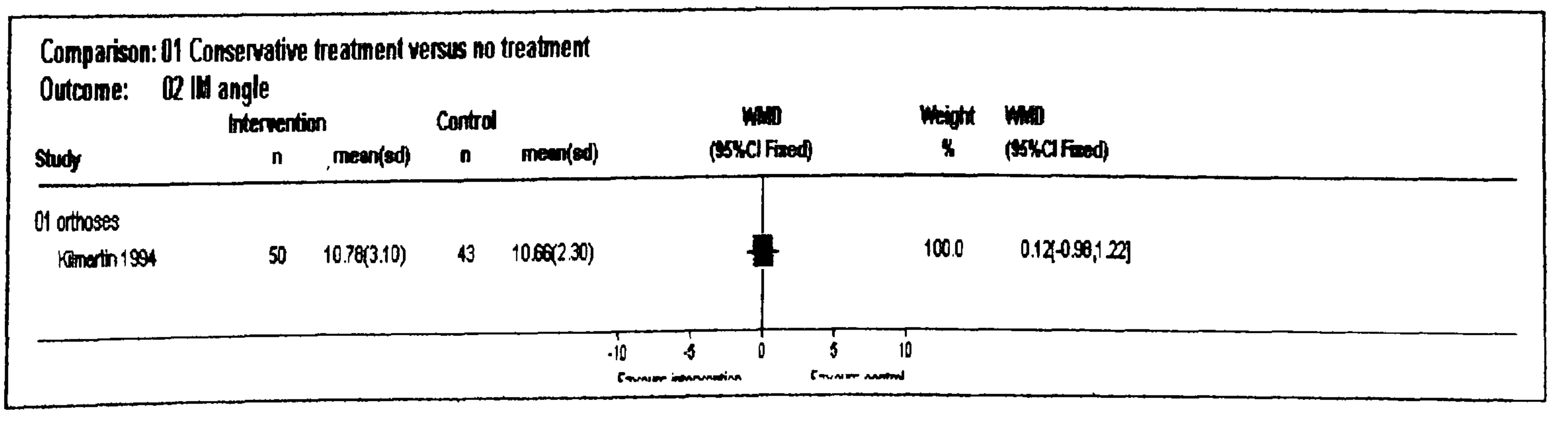
Figure 83. Comparsion of conservative treatment versus no treatment: HAV angle



b) Intermetatarsal (IM) angle

Kilmartin 1994 reported this outcome and there was no evidence of a difference between groups (MD = 0.12 degrees, 95% CI = -0.98 to 1.22 degrees). Thus the use of orthoses did not prevent deterioration in the IM angle (figure 84).

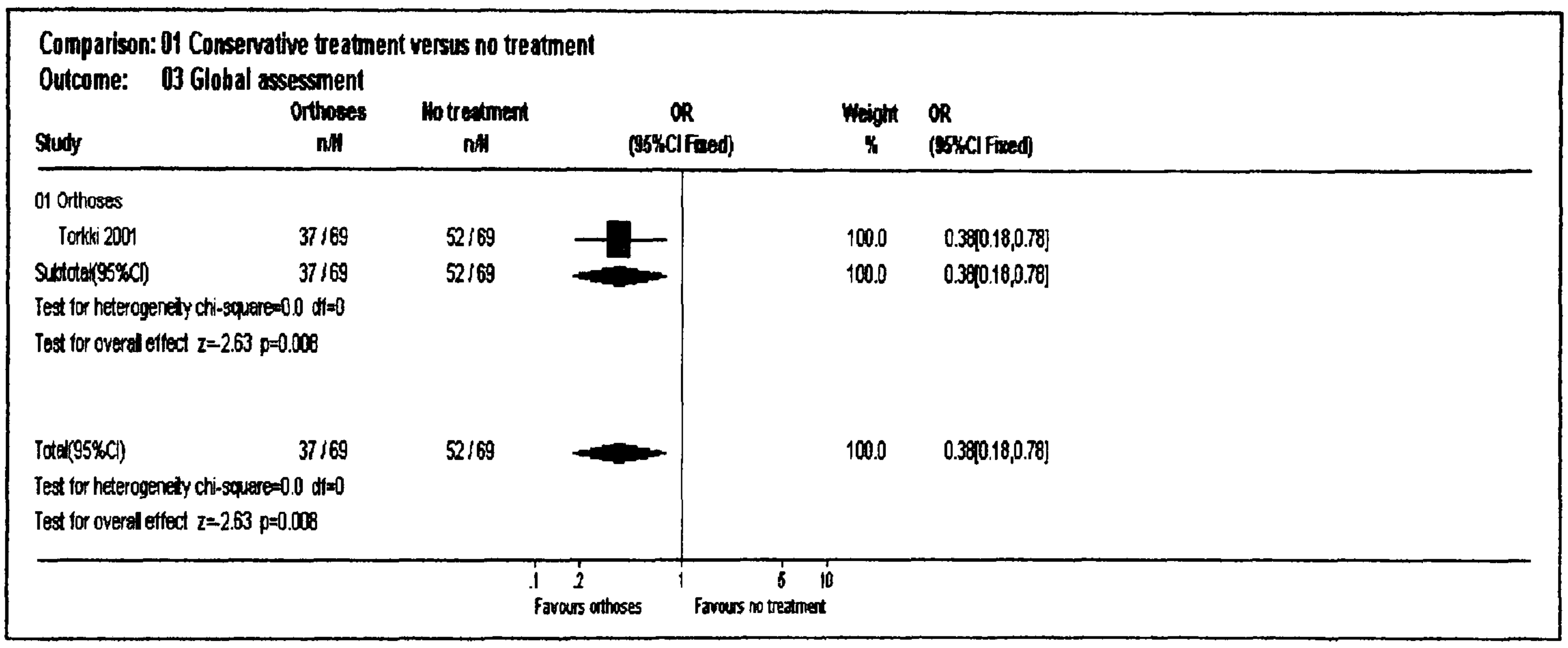
Figure 84. Comparsion of conservative treatment versus no treatment: IM angle



c) Global assessment

Torkki 2001 found evidence of a difference between the groups. In the no treatment group, there were more patients who considered themselves the same as or worse after a year than there were in the group who received orthoses (Odds Ratio (OR) = 0.38, 95% CI = 0.18 to 0.78)(figure 85).

Figure 85. Comparsion of conservative treatment versus no treatment: Global assessment



d) Functional assessment (AOFAS score)

Torkki 2001 reported this outcome. There was no evidence of a difference in this functional score between those receiving orthoses and those receiving no treatment (MD = -2, 95% CI = -5.34 to 1.34).

e) Pain

Juriansz 1996 and Torkki 2001 reported pain. In the trial by Juriansz 1996, there was no statistically significant difference detected between the numbers of participants remaining in pain when prescribed night splints compared with no treatment (OR = 2.20, 95% CI = 0.47 to 10.35). There was no evidence of a difference in the pain scores reported on a visual analogue scale in patients receiving orthoses and those receiving no treatment (MD = 0, 95% CI = -8.19 to 8.19) in the trial by Torkki 2001.

f) Satisfaction

Torkki 2001 reported this outcome through the use of a visual analogue scale. The participants receiving no treatment tended to be more dissatisfied at final follow up but the difference did not reach statistical significance (MD = 9.00, 95% CI = -1.81 to 19.81).

g) Number of patients requiring specialist footwear

Torkki 2001 found no evidence of a difference between the group receiving orthoses and those receiving no treatment for this outcome (OR = 1.72, 95% CI = 0.39 to 7.49).

CONSERVATIVE TREATMENT VERSUS CONSERVATIVE TREATMENT

No comparisons available

SURGICAL TREATMENT VERSUS CONSERVATIVE TREATMENT

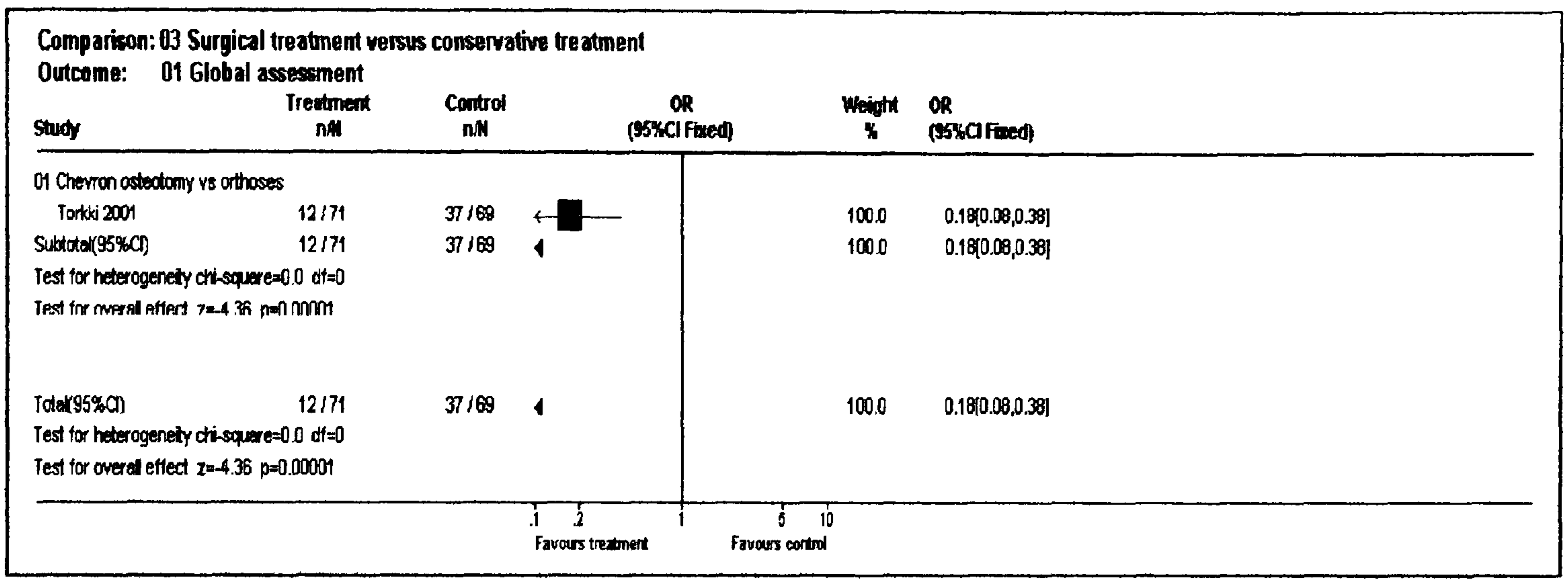
One trial of good method quality and size reported in this comparison.

Chevron osteotomy vs orthoses (Torkki et al., 2001)

a) Global assessment

Evidence was shown in favour of the surgery group. A statistically significant difference was found with fewer participants in the chevron group reporting that they were the same as or worse than one year ago compared with the orthoses group (OR = 0.18, 95% CI = 0.008 to 0.38)(figure 86).

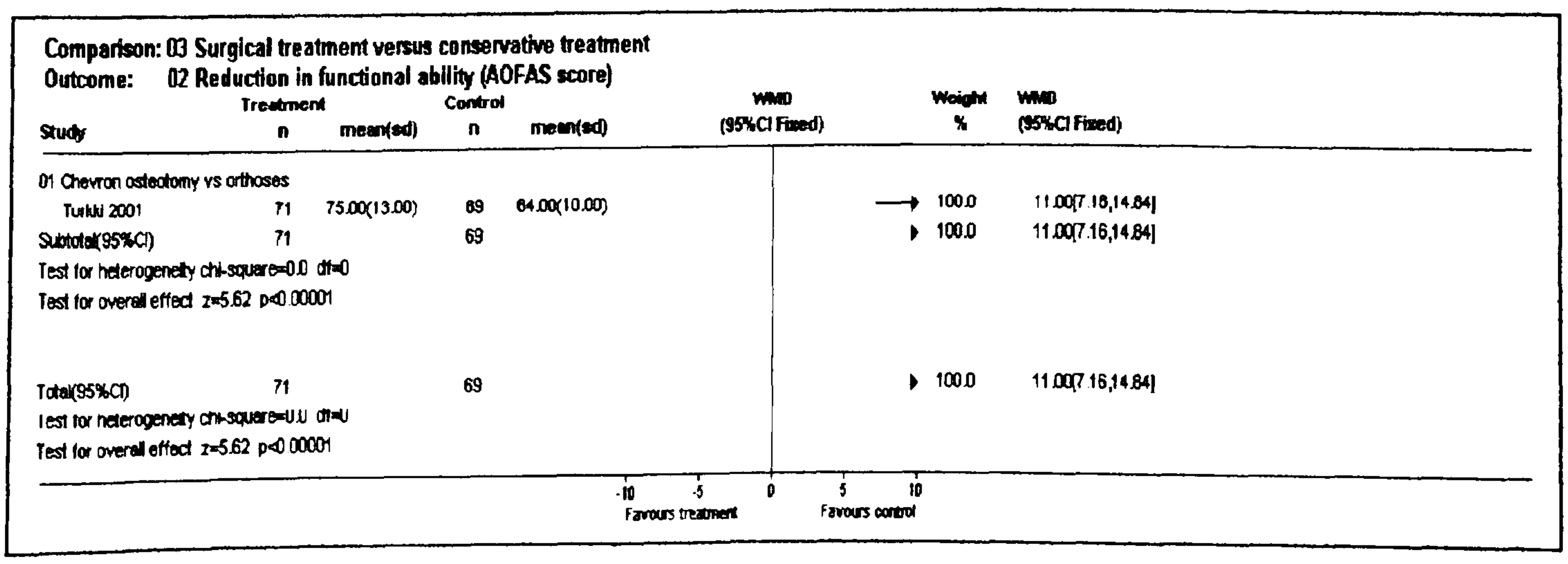
Figure 86. Comparsion of surgical treatment versus conservative treatment: Global assessment



b) Functional ability

Torkki 2001 showed evidence of a difference in the functional scores, in favour of the surgery group. There was a statistically significant lower score in the orthoses group compared to the surgery group (MD = 11.00, 95% CI = 7.16 to 14.84) (figure 87).

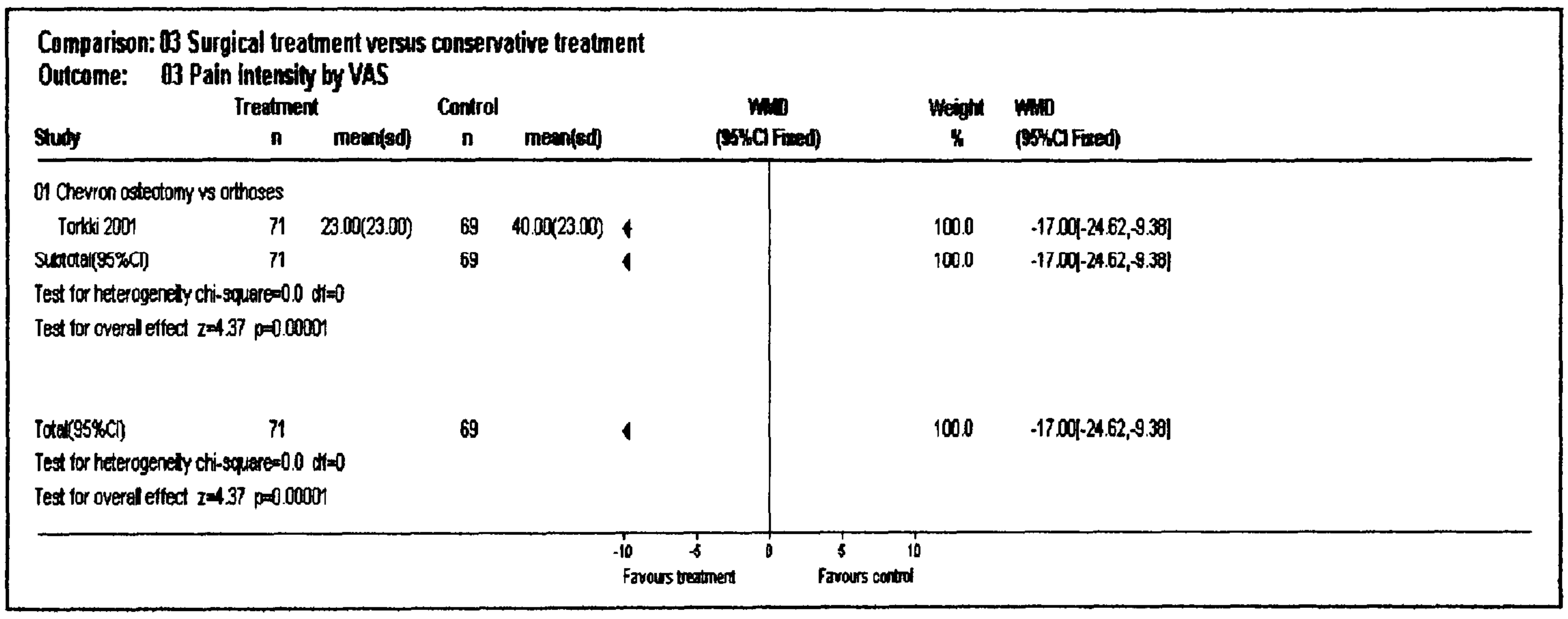
Figure 87. Comparsion of surgical treatment versus conservative treatment: AOFAS score



c) Pain

Torkki 2001 showed evidence of a reduction in pain in those patients receiving surgery compared with those patients receiving foot orthoses (MD = -17.00, 95% CI = -24.62 to -9.38) (figure 88).

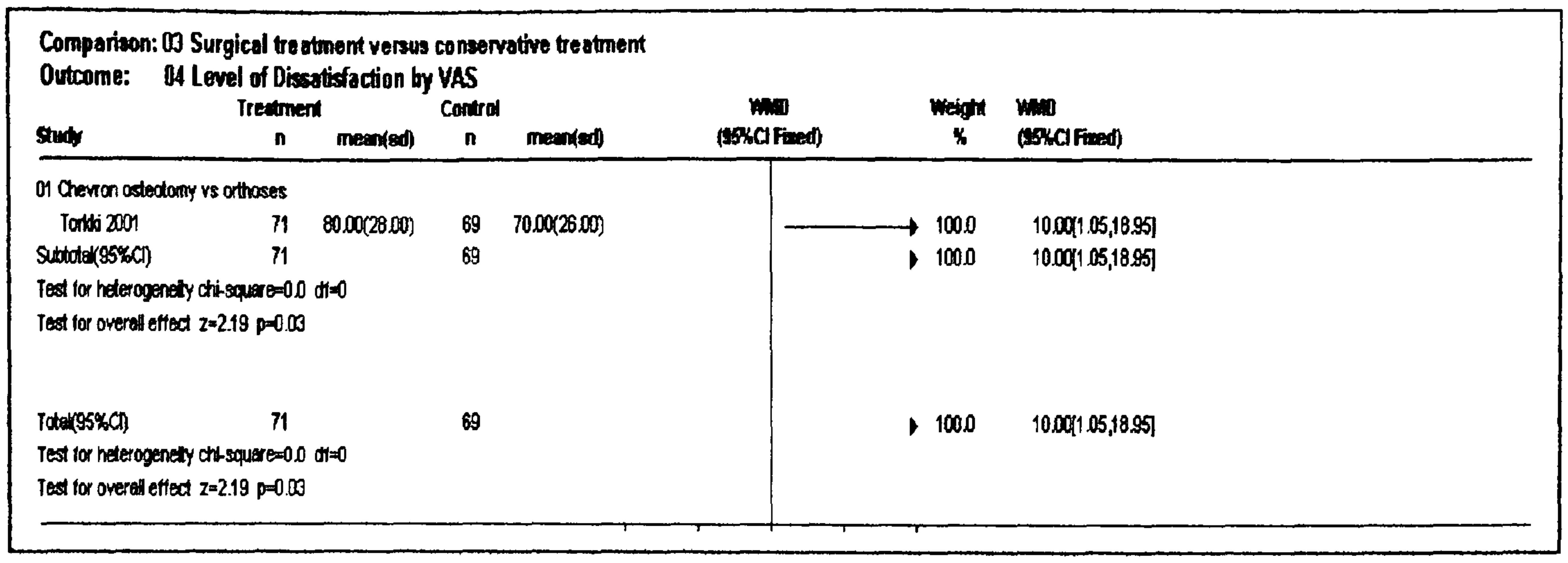
Figure 88. Comparsion of surgical treatment versus conservative treatment: Pain score



d) Satisfaction

This study showed evidence of greater levels of dissatisfaction in those participants being treated with orthoses compared with those in the chevron osteotomy group (MD = 10.00, 95% CI = 1.05 to 18.95) (figure 89).

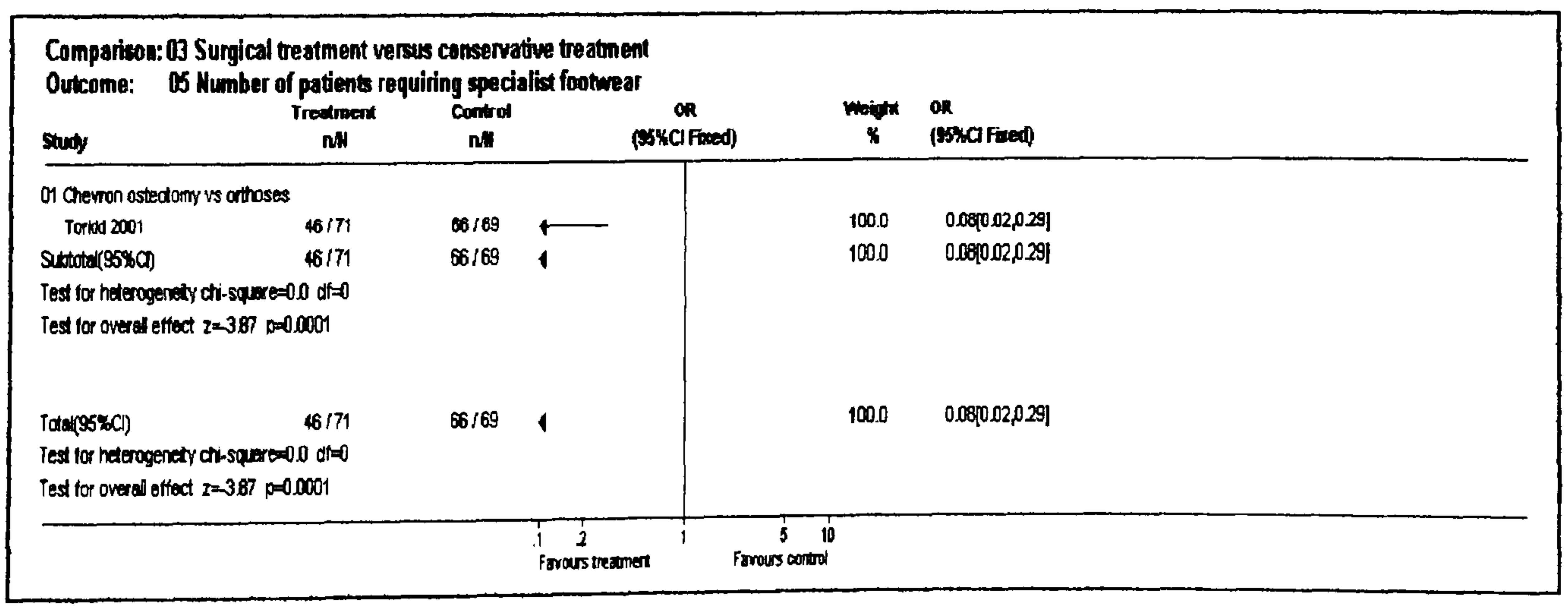
Figure 89. Comparsion of surgical treatment versus conservative treatment: Dissatisfaction



e) Number of patients requiring specialist footwear

Torkki 2001 showed evidence in favour of the surgery group. There was evidence that fewer participants in the surgical group required specialist footwear compared to those in the orthoses group (OR = 0.08, 95% CI = 0.02 to 0.29) (figure 90).

Figure 90. Comparsion of surgical treatment versus conservative treatment: Footwear



SURGICAL TREATMENT VERSUS NO TREATMENT

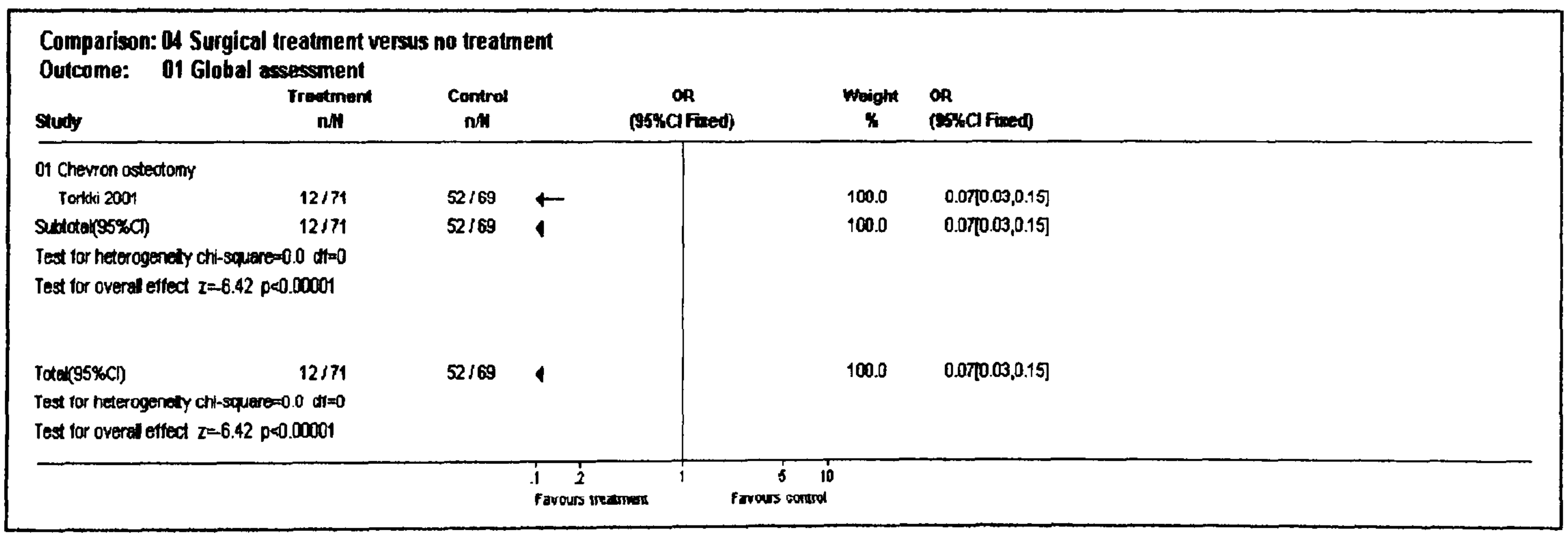
One trial of good method quality and size is reported in this comparison.

Chevron osteotomy vs no treatment (Torkki et al., 2001)

a) Global assessment

There was evidence that fewer participants receiving surgery reported themselves to be the same or worse than one year previously compared with those receiving no treatment (OR = 0.07, 95% CI = 0.03 to 0.15) (figure 91).

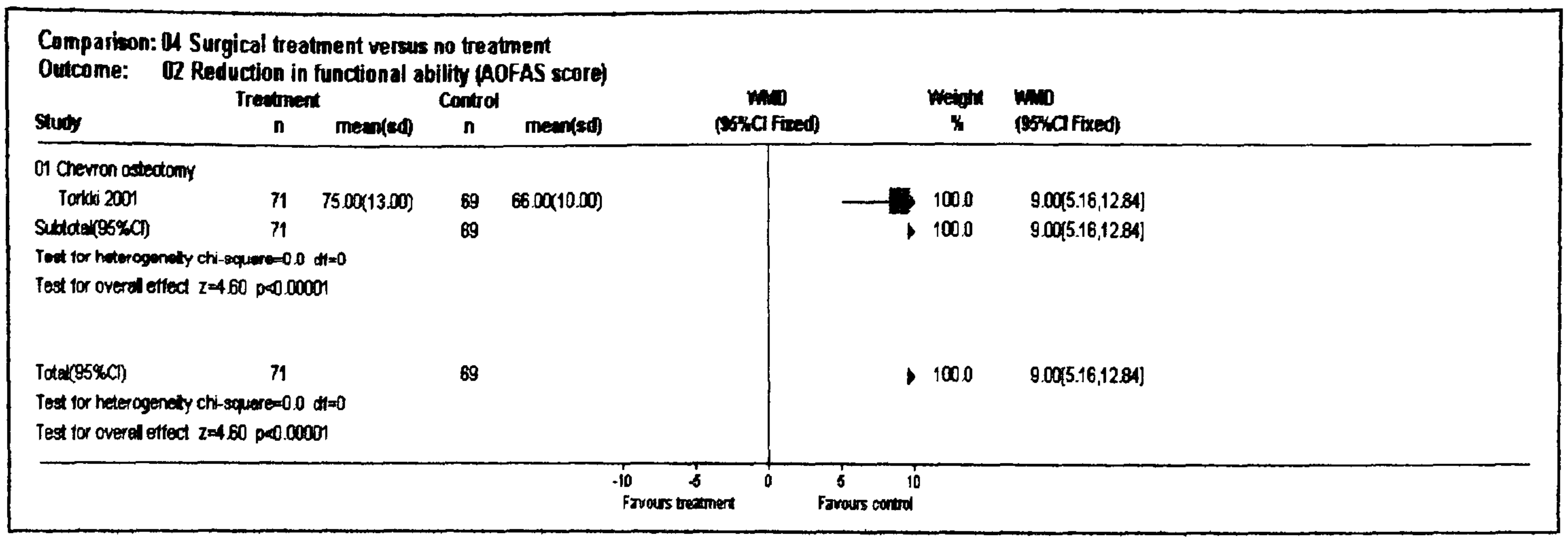
Figure 91. Comparsion of surgical treatment versus no treatment: Global assessment



b) Functional assessment (AOFAS score)

There was evidence of a statistically significant reduction in functional ability of the non-treatment group compared to the group receiving the chevron osteotomy at final follow-up (MD = 9.00, 95% CI = 5.16 to 12.84) (figure 92).

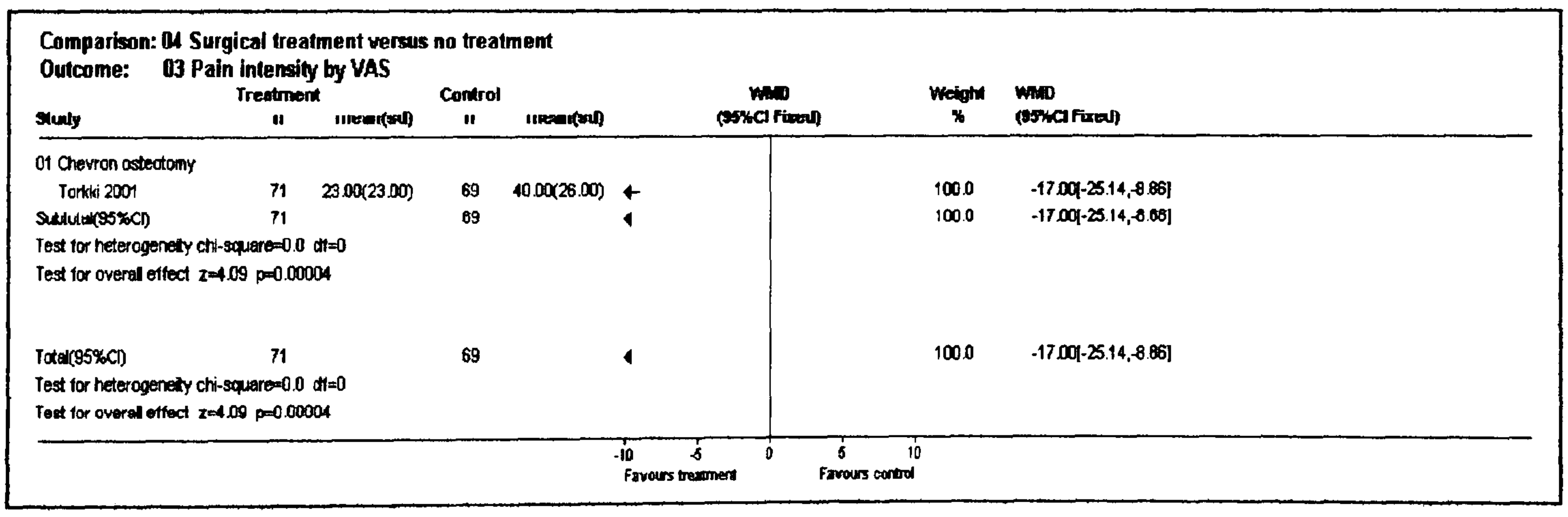
Figure 92. Comparsion of surgical treatment versus no treatment: AOFAS score



c) Pain

Torkki 2001 showed evidence of a difference in pain level, in favour of the surgery group (MD = -17.00, 95% CI = -25.14 to -8.86) (figure 93).

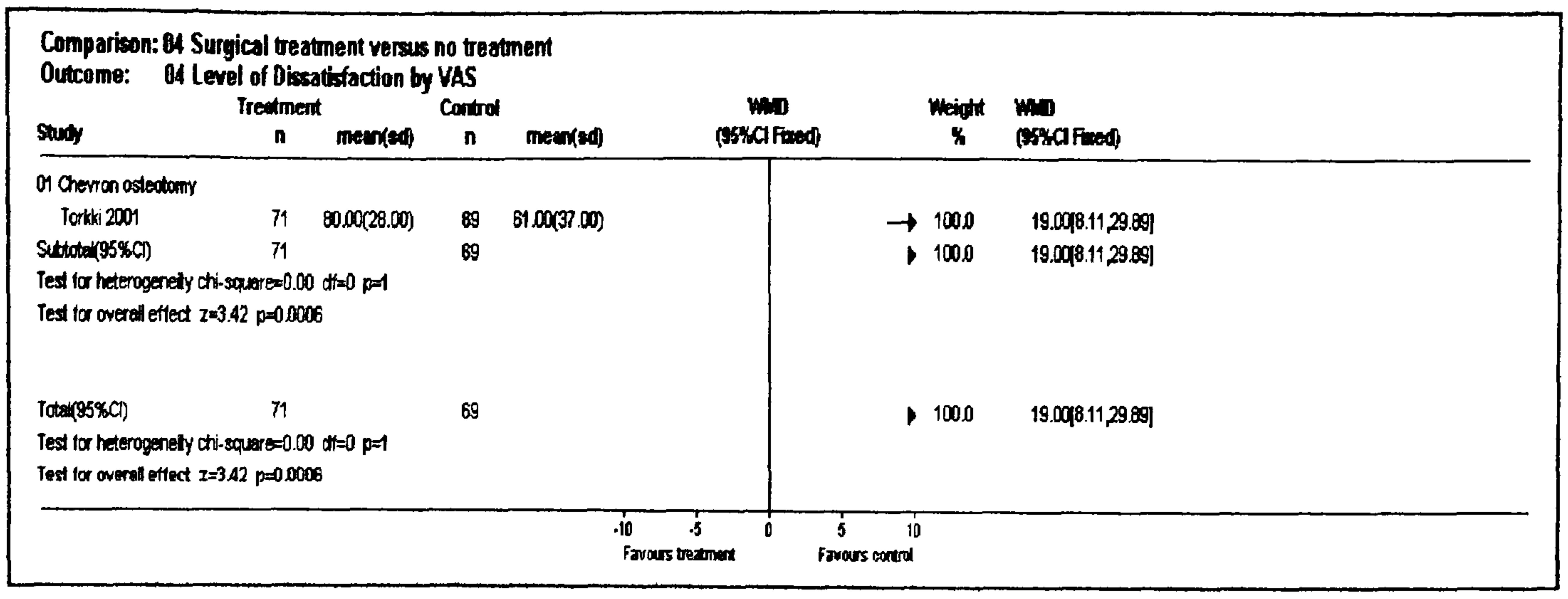
Figure 93. Comparsion of surgical treatment versus no treatment: Pain



d) Satisfaction

In this study, Torkki 2001 showed evidence of a low level of dissatisfaction in participants undergoing chevron osteotomy compared with no treatment after 12 months (MD = 19.00, 95% CI = 8.11 to 29.89) (figure 94).

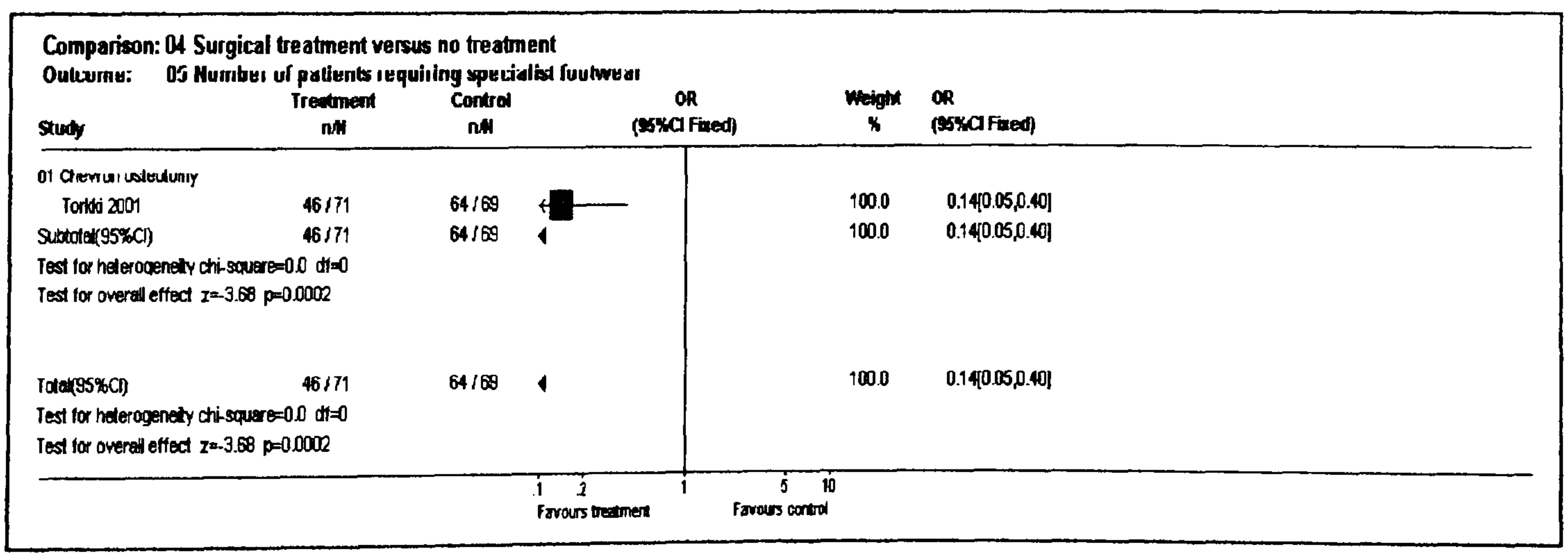
Figure 94. Comparsion of surgical treatment versus no treatment: Dissatisfaction



e) Footwear

Evidence was shown of a reduction in the number of patients requiring specialist footwear in the surgical group compared to those receiving no treatment (OR = 0.14, 95% CI = 0.05 to 0.40) (figure 95).

Figure 95. Comparsion of surgical treatment versus no treatment: Footwear



OTHER OPERATIVE PROCEDURE VERSUS KELLER'S ARTHROPLASTY

Two trials of poor method quality tested the following comparisons:

Arthrodesis versus Keller's arthroplasty (O'Doherty et al., 1990)

Distal osteotomy versus Keller's arthroplasty (Turnbull and Grange, 1986)

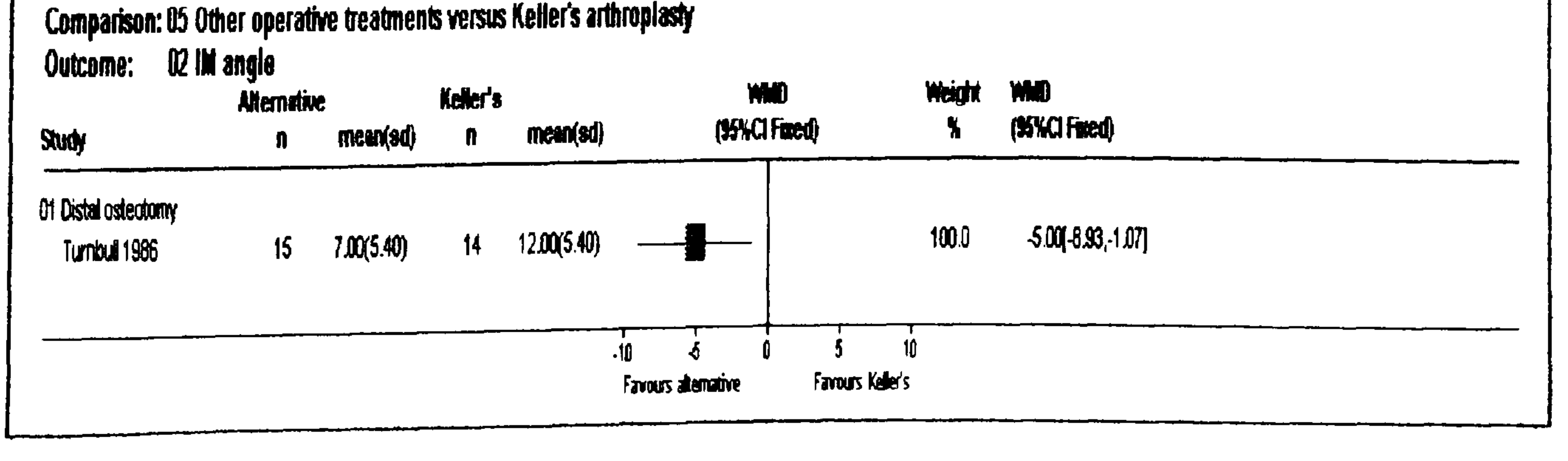
a) Hallux valgus angle

Both trials reported HV angle. There was no evidence of a difference in the final HV angle within any of the trials. O'Doherty 1990 reported identical outcome measurements for the arthrodesis and Keller's arthroplasty. Turnbull 1986 showed a greater reduction in HV angle at follow-up with the osteotomy, but this did not reach the level of statistical significance (MD = -9 degrees, 95% CI = -18.03 to 0.03 degrees).

b) Intermetatarsal angle

Only Turnbull 1986 reported the intermetatarsal angle as an outcome. Evidence of a difference in the reduction of the angle was shown in the group undergoing distal metatarsal osteotomy (MD = -5.00 degrees, 95% CI = -8.93 to -1.07 degrees). This is to be expected since Keller's arthroplasty only addresses the hallux whereas the osteotomy aims to realign the metatarsal (figure 96).

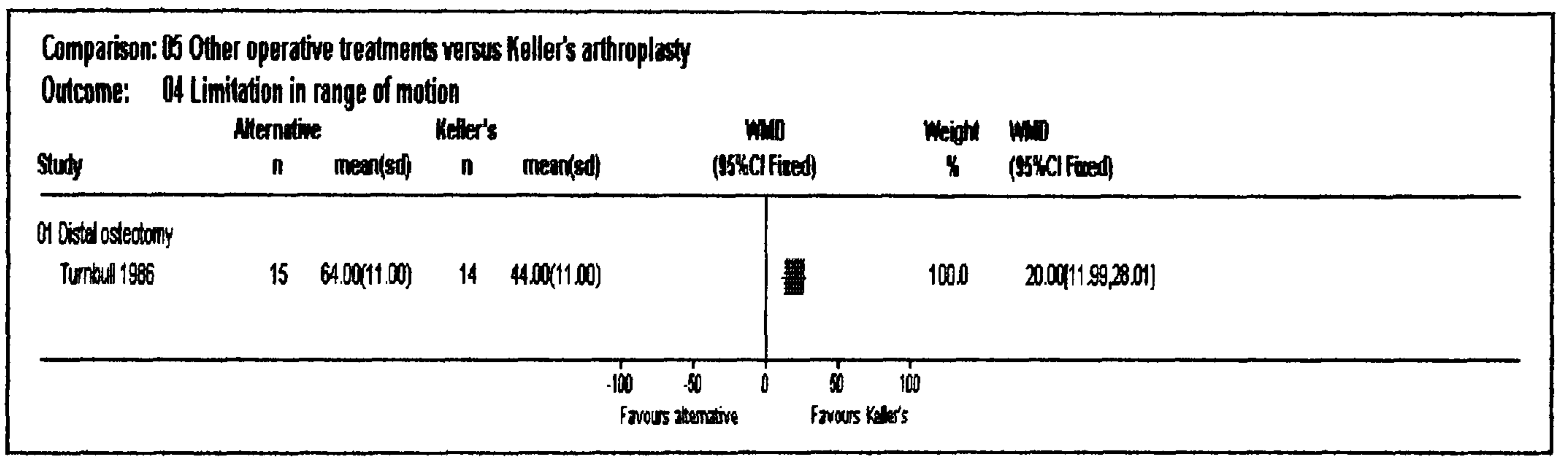
Figure 96. Comparison of other operative treatments versus Keller's arthroplasty: IM angle



c) Range of motion

Only Turnbull 1986 reported motion of the joint, showing evidence that a decrease in motion occurred in the group undergoing Keller's arthroplasty (MD = 20.00 degrees, 95% CI= 11.99 to 28.01 degrees). This result is unexpected with a Keller's operation, as a flexible toe should result. Weightbearing with exercises was allowed the day following the operation (figure 97).

Figure 97. Comparison of other operative treatments versus Keller's arthroplasty: ROM



d) Complications

O'Doherty 1990 did not provide information on post-operative complications but did present incomplete data for clinical symptoms such as 'cock-up' deformity (hyperextension at the interphalangeal joint), malunion and non-union. They reported that more participants in the Keller's group had 'cock-up', but that the difference was not statistically significant. No participants had marked 'cock-up' deformity of the hallux. O'Doherty 1990 also noted that 22 out of 50 feet (44%) in the arthrodesis group had non-union. Turnbull 1986 reported no evidence of difference in the number of patients with complications (all superficial wound infections) following osteotomy or Keller's arthroplasty (OR = 0.26, 95% CI = 0.02 to 2.88).

e) Pain

Both trials reported pain as an outcome. There was no evidence of a difference in the numbers of participants remaining in pain between the arthrodesis and Keller's arthroplasty (OR = 0.95, 95% CI = 0.23 to 3.81), and distal osteotomy and Keller's arthroplasty (OR = 0.91, 95% CI = 0.18 to 4.64). The numbers of patients remaining in pain at final assessment were relatively small.

f) Patient satisfaction

Both trials reported patient satisfaction. There was no evidence of a difference in the number of participants remaining dissatisfied between the arthrodesis and Keller's arthroplasty (OR = 1.11, 95% CI = 0.41 to 3.01), or the distal osteotomy and Keller's arthroplasty (OR = 0.91, 95% CI = 0.18 to 4.64). However, examination of the numbers of patients dissatisfied at final assessment shows that around 25% of patients were dissatisfied regardless of operation type. The number in pain was similar to the number dissatisfied in Turnbull 1986. In O'Doherty 1990, the number of participants dissatisfied exceeded the number in pain.

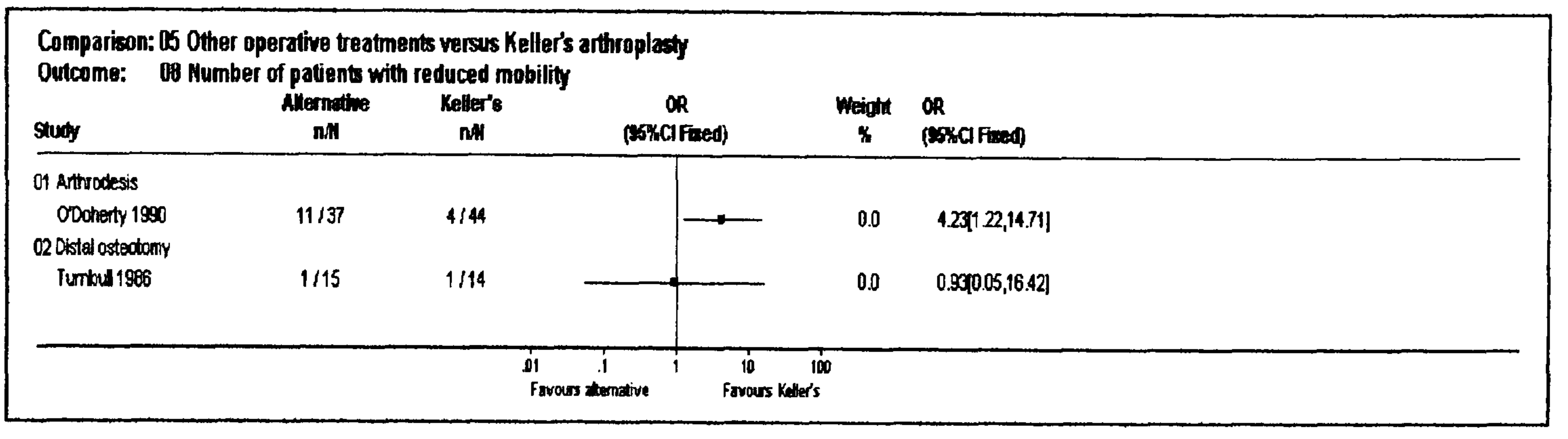
g) Footwear

O'Doherty 1990 reported this outcome. There was no evidence of a difference between the arthrodesis and Keller's arthroplasty in the number of participants requiring specialist footwear after treatment (OR = 1.27, 95% CI = 0.48 to 3.39).

h) Limited walking

Both trials reported the number of participants who had restricted walking after the operations. O'Doherty 1990 showed evidence that fewer participants had reduced mobility after the Keller's arthroplasty compared with the arthrodesis (OR = 4.23, 95% CI = 1.22 to 14.71). In Turnbull 1986, just one person had restricted walking in each group (OR = 0.93, 95% CI = 0.05 to 16.42) (figure 98).

Figure 98. Comparsion of other operative treatments versus Keller's arthroplasty: Mobility



OTHER OPERATIVE PROCEDURE VERSUS CHEVRON (AND CHEVRON-TYPE) OSTEOTOMY

Six trials of poor to moderate method quality tested the following comparisons:

Distal chevron comparisons:

Wilson osteotomy versus chevron osteotomy (Klosok et al., 1993)

Akin with distal soft tissue release (DSTR) versus chevron-Akin (Basile et al., 2000)

Proximal osteotomy with screw fixation versus chevron osteotomy with screw fixation (Partio et al., 1998).

Proximal chevron comparisons:

Proximal crescentic osteotomy versus proximal chevron osteotomy (Easley et al., 1996).

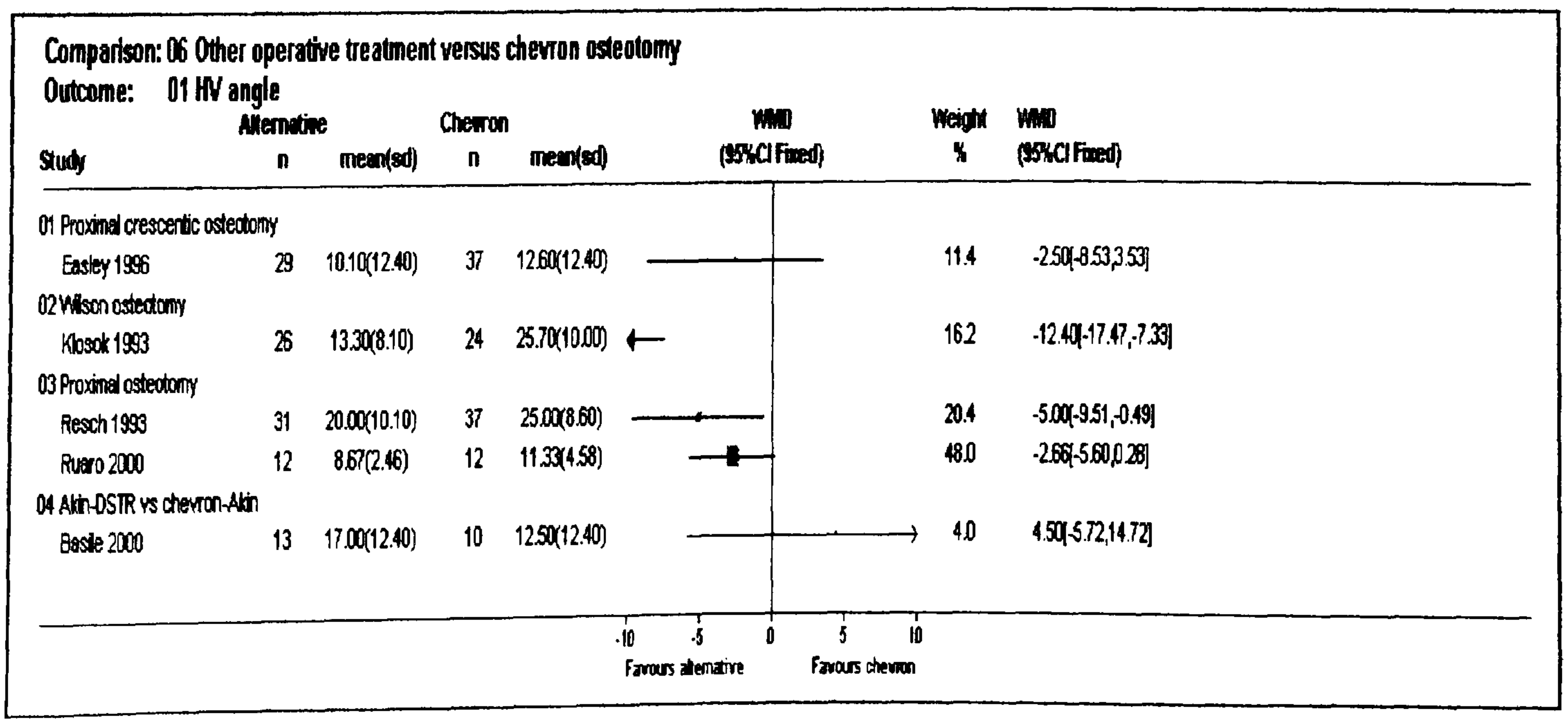
Proximal osteotomy versus proximal chevron osteotomy (Resch et al., 1993; Ruaro et al., 2000).

a) Hallux valgus angle

Five of the trials reported HV angle. The results showed evidence in favour of the alternative procedures for both Klosok 1993 and Resch 1993, showing statistically significant improvement in angle with the alternative operation: Wilson osteotomy (MD = -12.4 degrees, 95%CI = -17.47 to -7.33 degrees) and proximal osteotomy (MD = -5.00 degrees, 95% CI = -9.51 to -0.49 degrees) respectively. The trial by Basile 2000 found in favour of the chevron-Akin procedure but the difference between the groups was not statistically significant (MD = 4.5 degrees, 95% CI = -5.77 to 14.72 degrees) (figure 99).

Easley 1996 and Ruaro 2000 showed no evidence of a difference between the proxiaml chevron and the proximal cresentic ostoeotomy (MD = -2.50 degrees, 95%CI = -8.53 to 5.53 degrees) or the proximal osteotomy (MD = -2.66 degrees, 95%CI = -5.60 to 0.28 degrees).

Figure 99. Comparison of operative treatments versus chevron osteotomy: HAV angle



b) Intermetatarsal angle

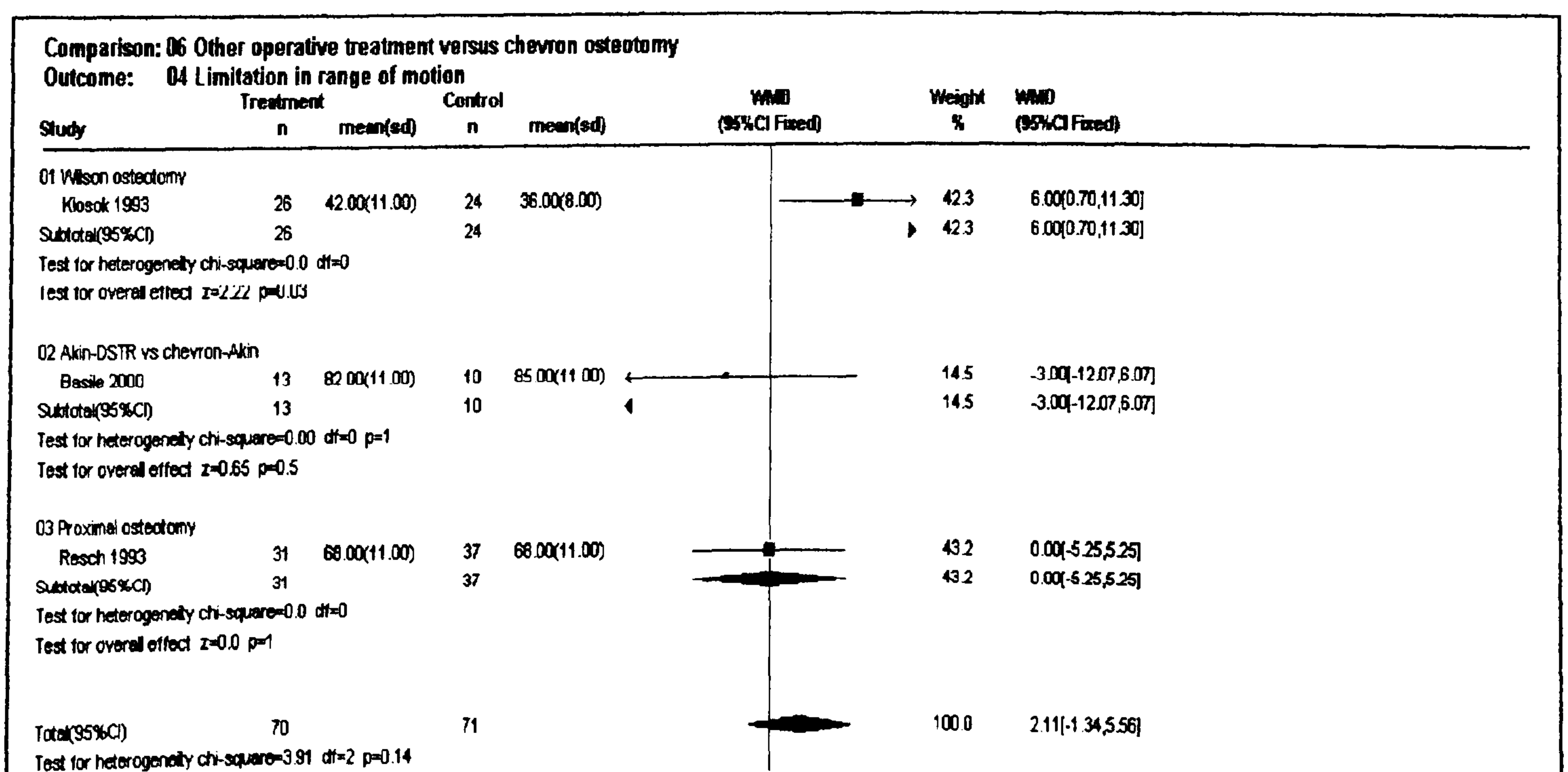
Resch 1993 amd Basile 2000 considered this outcome. Only Resch 1993 showed evidence of an improvement in angle with the proximal osteotomy significantly improving the IM angle compared with the chevron procedure (MD = -3.00 degrees, 95% CI = -5.00 to -1.00 degrees).

Easley 1996 and Ruaro 2000, in their comparisons of proximal procedures, showed no evidence of a significant difference in procedures for this outcome.

c) Range of motion

Klosok 1993 showed evidence of a difference in the range of motion in favour of the Wilson osteotomy (MD = 6 degrees, 95% CI = 0.7 to 11.3 degrees). In Resch 1993 and Basile 2000, no statistically significant differences were detected between treatment groups (MD = 0 degrees, 95% CI = -5.25 to 5.25 and MD = -3.00 degrees, 95% CI = -12.07 to 6.07 degrees respectively) (figure 100).

Figure 100. Comparison of operative treatments versus chevron osteotomy: ROM



d) Complication rate

Five trials considered this outcome. There was no evidence of a difference in the number of complications in the trials - Klosok 1993 (OR = 1.22, 95% CI = 0.39 to 3.80), Basile 2000 (OR = 0.33, 95% CI = 0.03 to 4.32) or Partio 1998 (OR = 2, 95% CI = 0.44 to 9.19).

Easley 1996 nor Ruaro 2000 showed evidence of a difference in the comparison of proximal procedures (OR = 0.76, 95% CI = 0.22 to 2.61). or (OR = 2.20, 95% CI = 0.17 to 28.14) respectively.

e) Functional assessment (AOFAS score)

Ruaro 2000 found that the proximal chevron procedure produced the higher score, indicative of improved function, but a statistically significant difference between the groups was not detected (MD = -3, 95% CI = -6.02 to 0.02).

Easley 1996 used this outcome. No evidence of a difference in functional scores was shown at follow up (MD = 2.00, 95% CI = -4.32 to 8.32).

f) Pain

Only Resch 1993 and Basile 2000 reported pain. Resch 1993 found there was no evidence of difference in the number of participants remaining in pain between the treatments (OR = 0.55, 95% CI = 0.13 to 2.42). Basile 2000 also found no evidence of a difference between operations (OR = 1.46, 95% CI = 0.25 to 8.43).

g) Patient satisfaction

Two trials reported this outcome (Resch 1993 and Basile 2000). Resch 1993 found there was no evidence of a difference in the number of patients dissatisfied at outcome

(OR = 0.99, 95% CI = 0.36 to 2.75). It was notable that in both groups, 33% of the patients remained dissatisfied. Basile 2000 showed a non-significant trend towards the Akin-DSTR group for this outcome (OR = 0.27, 95% CI = 0.04 to 1.95).

h) Footwear

Klosok 1993 and Resch 1993 reported footwear problems. There was no evidence of a difference in the number of participants requiring specialist footwear (OR = 0.26, 95% CI = 0.06 to 1.14) and (OR = 0.38, 95% CI = 0.04 to 3.83) respectively.

i) Limited walking

Klosok 1993 and Resch 1993 considered walking difficulties. There was no evidence of a difference between the number of participants with reduced mobility (OR = 0.69, 95% CI = 0.16 to 2.95) and (OR = 0.38, 95% CI = 0.04 to 3.83) respectively.

SURGEON'S ADAPTATION VERSUS ORIGINAL OPERATION

Three trials of moderate method quality were included in this group:

Keller-Lelieve's (K-L) operation with tendon transfer versus K-L operation (Capasso et al., 1994)

Chevron osteotomy plus tenotomy versus chevron osteotomy (Resch et al., 1994)

Keller's operation with distraction (using temporary Kirschner wire) versus Keller's operation (Sherman et al., 1984)

a) Hallux valgus angle

All three trials compared this outcome. There was no evidence of a difference in the final HV angle between the original operation and the surgeon's adaptation for any trial:

Capasso 1994: MD = 1.30 degrees, 95% CI = -7.44 to 10.03 degrees

Resch 1994: MD = -3.30 degrees, 95% CI = -8.63 to 2.03 degrees

Sherman 1984: MD =0 degrees, 95% CI = -4.48 to 4.48 degrees.

b) Intermetatarsal angle

No trial considered this outcome.

c) Range of motion

Resch 1994 reported on range of motion. No evidence of a difference in motion was found following the addition of a tenotomy to the original operation (MD = -2.00 degrees, 95% CI = -6.73 to 2.73 degrees).

d) Complication rates

All three trials recorded complications. There was no evidence of a difference in the number of complications following the modified Keller-Lelieve operation (OR = 1.50, 95%CI = 0.21 to 10.52) or chevron osteotomy plus tenotomy (OR = 1.89, 95% CI = 0.30 to 11.91). Sherman 1984 reported one delayed wound healing in each group.

e) Pain

All three trials considered pain. No evidence of a difference in the number of patients remaining in pain between the surgeon's adaptation and the original operation was found in each case.

Capasso 1994: OR = 0.30, 95% CI = 0.07 to 1.33

Resch 1994: OR = 1.78, 95% CI = 0.56 to 5.67

Sherman 1984: OR = 1.01, 95% CI = 0.29 to 3.55.

Where reported, approximately 25% of patients remained in pain at the end of the study.

f) Patient satisfaction

There was no evidence of a difference in numbers of participants remaining dissatisfied in Resch 1994 (OR = 1.99, 95% CI = 0.68 to 5.87), but as noted previously, one quarter of both groups remained dissatisfied at the final follow-up. Sherman 1984 reported that there was no difference between the two groups in terms of overall satisfaction. However, it was noted that several patients of the distraction group had found the Kirschner wire unpleasant and most had feared its removal.

g) Footwear

Capasso 1994 and Resch 1994 recorded the number of participants reporting difficulties with footwear. Only a small number of the total group required specialist footwear and a statistically significant difference between the groups was not detected:

Capasso 1994: (OR = 0.57, 95% CI = 0.08 to 4.01)

Resch 1994: (OR = 0.31, 95% CI = 0.06 to 1.59)

Although the mean time before returning to wearing normal shoes was less in the distraction group (11 versus 15 weeks) in Sherman 1984, the removal of data from the one person, who was still not wearing normal shoes in the control group at one year, actually reversed the direction of effect.

h) Limited walking

Resch 1994 considered mobility as an outcome. There was no evidence of a difference in the number of participants with reduced mobility between the chevron osteotomy and the chevron plus tenotomy (OR =1.22, 95% CI = 0.07 to 20.12).

NEW METHOD OF FIXATION VERSUS ORIGINAL METHOD OF FIXATION

Three trials of generally moderate and good method quality were included in this group:

Screw fixation versus suture fixation of Mitchell's osteotomy (Calder et al., 1999)

Absorbable polydioxanone pins versus suture or K-wire in Mitchell's osteotomy (Prior et al., 1997)

Self reinforced PLLA screws versus self reinforced PDLLA screws in proximal osteotomy or arthrodesis (Joukainen et al., 1998)

In the study by Joukainen 1998, the data were lacking in the number of participants analysed.

a) Hallux valgus angle

Both trials considered this outcome. Calder 1999 found no evidence of a difference between the fixation techniques in respect of this outcome (MD = 1.20 degrees, 95% CI = -2.35 to 4.7 degrees). In Prior 1997, no evidence was found of a difference between the groups (MD = 1.20 degrees, 95% CI = -4.81 to 9.61 degrees).

b) Intermetatarsal angle

There was no evidence of an effect of the fixation technique on this outcome. Calder 1999 found no statistically significant difference between the techniques (MD = 1.60 degrees, 95% CI = -1.46 to 4.66 degrees) and Prior 1997 also found no statistically significant difference (MD = 0.30 degrees, 95% CI = -1.77 to 2.37 degrees).

c) Range of motion

There was no evidence of an effect on the motion at the joint when absorbable screws were compared to sutures or K-wire (Prior 1997) (MD = -3.70 degrees, 95% CI = -19.02 to 11.62 degrees).

d) Complications

No evidence of an effect of the method of fixation was shown. Calder 1999 found fewer patients in the suture group had complications, but the result was not statistically significant (OR = 5.09, 95% CI = 0.5 to 52.29). Prior 1997 found fewer complications in the absorbable screw group but the result was not statistically significant (OR = 0.44, 95% CI = 0.07 to 2.28).

e) Pain

There was no evidence of a difference between the fixation technique used in the pain level at follow up (Prior 1997) (OR = 0.73, 95% CI = 0.04 to 13.05).

f) Satisfaction

There was no evidence of a difference between the fixation technique used in the satisfaction level at follow up (Prior 1997) (OR = 1.7, 95% CI = 0.13 to 19.67). Calder 1999 found no patients to be dissatisfied at 1 year follow up.

g) Footwear

Prior 1997 reported this outcome. There was no evidence of a difference on the number of patients having difficulty with normal footwear (OR = 1.57, 95% CI = 0.13 to 19.67).

h) Limited walking

There was no evidence of a difference in the number of participants having difficulty walking after absorbable pin fixation compared with suture or K-wire fixation (Prior 1997) (OR = 0.73, 95% CI = 0.04 to 13.05).

COMPARISONS OF POST-OPERATIVE REHABILITATION REGIMENS

There were three trials of moderate method quality in this group:

Continuous passive motion (CPM) plus routine physiotherapy versus routine physiotherapy, after an Austin procedure (Connor et al., 1995)

Early versus late weightbearing after arthrodesis (Lampe et al., 1991)

Crepe bandage vs plaster slipper after first metatarsophalangeal joint fusion (Meek and Anderson, 1998)

Crepe bandage vs plaster slipper after Wilson's osteotomy (Meek and Anderson, 1999)

a) Hallux valgus angle

Meek 1998 and Meek 1999 considered this outcome. There was no evidence of a difference in the hallux valgus angle at 3 months between being given a plaster slipper or crepe bandage after surgery (Arthrodesis: MD = -1.27 degrees, 95% CI = -5.16 to 2.62 degrees; Wilson's osteotomy: MD = -1.50 degrees, 95% CI = -4.47 to 1.47 degrees).

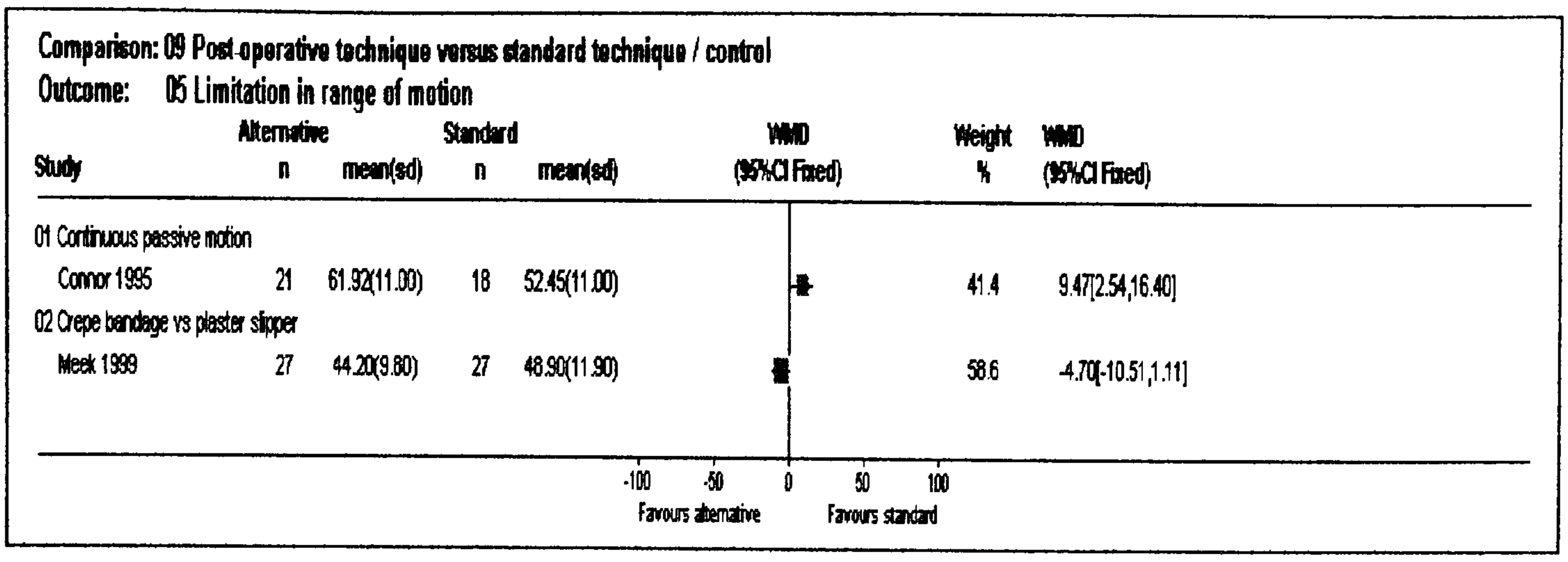
b) Intermetatarsal angle

Meek 1999 and Meek 1998 showed no evidence of a difference in outcome between the groups (Wilson's osteotomy : MD = -1.50 degrees, 95% CI = -4.47 to 1.47 degrees; Arthrodesis: MD = -0.50 degrees, 95% CI = -2.43 to 1.43 degrees).

c) Range of motion

The trial of continuous passive motion (Connor 1995) showed evidence of a statistically significant limitation in range of movement of the first metatarsophalangeal joint in the group undergoing physiotherapy only, compared to the group that received CPM plus physiotherapy (MD = 9.47 degrees, 95% CI = 2.54 to 16.40 degrees). Meek 1999 showed no evidence of a difference between post operative treatments (MD = -4.70 degrees, 95% CI = -10.51 to 1.11 degrees) (figure 101).

Figure 101. Comparison of post-operative techniquess versus standard technique: ROM



d) Complications

No statistically significant differences between the treatment groups were detected for this outcome. Connor 1995 reported that no complications occurred in either group. Lampe 1991 found no evidence of a difference in incidence of non-union when participants were allowed to bear weight early, compared with later weightbearing (OR = 0.69, 95% CI = 0.11 to 4.51). Meek 1998 found one case of failed correction and one non-union in the crepe bandage group and three failed corrections, four non-unions in the plaster group. There was no evidence of a difference between the groups (OR = 0.33, 95%CI = 0.06 to 1.97) Meek 1999 found two cases of wound infection in the slipper group, and one non-union, and one failed correction in the crepe bandage group. The overall number of complications showed no statistically significant difference between the groups (OR = 0.48, 95% CI = 0.04 to 5.64).

e) Pain

Connor 1995 recorded the use of oral analgesics. More patients in the CPM group had discontinued oral analgesics by seven days (19/21 versus 13/18). All patients had ceased oral analgesics by 14 days. Meek 1998 compared the pain levels through the use of a 0 - 10 VAS. No evidence of a difference was shown between the use of crepe bandage or plaster slippers (MD = -1.0, 95% CI = -2.01 to 0.01).

f) Satisfaction

Meek 1998 compared the satisfaction levels through the use of a 0 - 10 VAS. No evidence of a difference was shown between the use of crepe bandage or plaster slippers (MD = 1.0, 95% CI = -0.18 to 2.18).

g) Footwear

Connor 1995 recorded the time to return to conventional footwear. The mean time to return to conventional shoes was reported as being significantly shorter in the CPM group. Meek 1998 and Meek 1999 showed no evidence of a difference in patients requiring specialist footwear between the groups (Arthrodesis: OR = 0.46, 95% CI = 0.11 to 1.94; Wilson's osteotomy: OR = 0.13, 95% CI = 0.02 to 1.21).

h) Limited walking

Meek 1998 and Meek 1999 considered this outcome. No statistical difference between the groups was detected (Arthrodesis: OR = 0.33, 95% CI = 0.06 to 1.97; Wilson's osteotomy: OR = 0.48, 95% CI = 0.04 to 5.64).

6.27 Discussion

Evidence of an effective treatment for HAV deformity

Only a few of the large number and variety of interventions used in the treatment of hallux abductovalgus (HAV) have been evaluated within randomised controlled trials. Many of the 100 operations for HAV are adaptations of a core set of basic operations. Even so, most of the most frequently used basic operation types have not been compared with each other within randomised trials. Many of the trials are only applicable to particular patient groups. For example, because the Keller's arthroplasty is reported to disrupt 1st metatarsophalangeal joint function, it is used only in elderly patients and it is therefore impossible to compare it to techniques used in younger patients such as a soft tissue reconstruction. The distal osteotomies are reserved for deformities involving a low intermetatarsal angle because the correction achieved is not large. A greater correction is achieved when a proximal osteotomy is used. It was therefore not appropriate to pool the data from the trials in a Meta-analysis and there were insufficient trials of the same type to apply subgroup analysis. Overall there was sparse evidence that any one treatment technique was superior to another.

Conservative treatment

Two trials (Kilmartin 1994; Juriansz 1996) evaluating conservative treatment versus no treatment, showed no evidence of improvement in hallux valgus (HV) angle, or intermetatarsal (IM) angle, in the groups allocated to orthoses or night splints compared with the control groups. Kilmartin *et al* (1994) had also noted a non-significant trend for the unaffected foot in unilateral cases of HAV deformity to deteriorate more quickly in the orthoses group and suggested that this type of orthosis may be detrimental in juvenile HAV deformity. Unfortunately Torkki (2001) did not measure the HV angle or IM angle in the orthoses or no treatment groups of his study and so it cannot be seen if orthoses prevent or enhance the progression of the deformity in adults. All three trials found no difference in pain between the treatment and control groups. Torkki did however find evidence that the patients with orthoses were better, in terms of their global assessment, after 1 year. This may be a placebo effect, given that the patients' function, pain or footwear outcomes showed no differences. It may be that the outcomes used were not sufficiently sensitive to identify the affects of the orthoses or were not measuring the appropriate factor. It is unclear in Torrki's study how many subjects had a biomechanical abnormality causing HAV deformity. It would not be surprising to find that orthoses had no effect on outcomes overall if many of the patients did not require orthoses. However, the evidence to date suggests that, until proven otherwise, the conservative treatments used in these trials should not be used routinely for reduction or control of hallux valgus deformity. This may be difficult for the clinicians prescribing such devices to accept. From experience, most foot specialists would agree that conservative measures do not improve HAV deformity. That orthoses may make the HV angle worse is also considered unlikely but remains a possibility. However, since HAV deformity is so frequently considered to be caused by poor foot mechanics, it will be difficult to persuade people not to address the mechanics with orthoses. Since the publication of Kilmartin's paper which considered juvenile HAV only, there has been considerable discussion regarding the suitability of the orthoses prescribed. Indeed, the rationale for the orthoses does not appear to be based on earlier findings, by the same author, on the foot mechanics associated with juvenile HAV. Kilmartin *et al* (1994) had earlier described juvenile HAV in association with a plantarflexed 1st ray. The orthoses prescribed would not have controlled the 1st ray position and indeed in the published trial, Kilmartin doubts the etiology of HAV deformity being that of abnormal pronation despite prescribing anti-pronatory orthoses in the study.

In a situation where a foot is symptomatic, but surgery is not appropriate, orthoses aimed to specifically reduce pain are often prescribed but again, the evidence presented in this review suggests that the such devices were not effective.

Surgery versus no treatment

Surgery versus orthoses

The single trial that compared these treatments (Torkki 2001) found evidence that all outcomes improved significantly in the surgery group. Surgery gave approximately a 10 per cent improvement in function and a 50 per cent improvement in pain over the other treatments. Since shoe fitting and global assessments also showed evidence of an improvement after surgery, it was not surprising to find increased satisfaction levels in the surgery group. The duration of surveillance was only 1 year in this trial, which was sufficient to see immediate improvements in outcome, but long-term follow up would also be beneficial in evaluating the surgery. HAV deformity may reoccur if the causative factors are not removed and it would be interesting to observe the differences in outcome compared with orthoses and no treatment after a longer review period.

Surgical treatment

Only a few of the potential comparisons of surgical treatments were evaluated in randomised trials.

Keller's arthroplasty

There did not appear to be any advantage or disadvantage in using the Keller's arthroplasty over an arthrodesis or osteotomy. Limited evidence from one trial indicated that the distal osteotomy improved HV and IM angles as well as retaining the range of joint motion when compared with the Keller's arthroplasty. This is plausible; while the Keller's arthroplasty is considered to be a safe and easy operation, it may have a large impact on foot function (Mann and Coughlin, 1999). The removal of the first metatarsophalangeal joint is said to cause dysfunction of the sesamoid complex and weakening of the short flexor muscle (Hutton and Dhanendran, 1990). The foot is rendered weak in propulsion and transfer lesions would be expected to occur laterally so the operation is generally not recommended for the young, active person (Mann and Coughlin, 1999). An osteotomy, by preserving the joint, should not result in such dysfunction and because the primary deformity is addressed (high IM angle), the hallux position should not deteriorate in the long term. It is sometimes considered that the IM angle will improve after a Keller's arthroplasty because the deforming force of the hallux against the metatarsal is removed. This did not appear to occur in the study by Turnbull (1986) when the IM angle after the Keller's arthroplasty improved by just one degree.

Range of motion was lost with the Keller's arthroplasty when compared with the distal osteotomy. Although the Keller's operation often results in a flaccid toe joint immediately postoperatively, fibrosis may occur over time resulting in a more rigid toe. If the toe is poorly positioned after the arthroplasty or due to deforming forces when weightbearing, the hallux may remain in a dorsiflexed position. This results in the common 'cock-up' deformity. O'Doherty *et al* (1990) reported that 'cock-up' was more common, but not statistically significantly so, in the Keller's group. Despite the limited range of movement at the metatarsophalangeal joint that occurred after the Keller's arthroplasty compared to the osteotomy, the reduced movement still appeared to be better than no movement when considering the numbers of patients with limited mobility after the arthrodesis. Though data from all participants reported in O'Doherty were included in this review, there was some confusion regarding the inclusion of patients with hallux rigidus. It was unclear whether all patients had hallux valgus, with part of the group having a rigid joint whilst others had a flexible joint, or if the group included the two very different conditions. Furthermore, the choice of a wire to maintain toe position in the arthrodesis was probably inferior to screw fixation across the joint surface which is a more frequently used technique. The overall result of poor performance of the Keller's arthroplasty compared with the osteotomy is reflected in present practice where an osteotomy is the operation of choice. The Keller's arthroplasty is undertaken much less frequently nowadays but may have a role in the appropriate patient (Mann and Coughlin, 1999).

Chevron osteotomy

The chevron osteotomy did not appear to have better outcomes when compared to the other osteotomies. The chevron, in some trials, produced less favourable outcomes in terms of HV and IM angles, although the differences did not reach a level of significance. This may be due to the chevron osteotomy usually being reserved for mild deformity. Proximal osteotomies are used for more marked deformity because a greater angle of correction can be gained by pivoting the metatarsal at the base when compared with moving it at the neck. Thus it may be inappropriate to compare distal osteotomies (chevron) to proximal osteotomies unless the trial population excludes patients with marked IM angles. In Resch 1993, which compared proximal osteotomy with chevron osteotomy, patients with high IM angles were not excluded. Easley *et al* (1996) and Ruaro *et al* (2000) made more suitable comparisons between types of proximal osteotomy and the proximal chevron. These trials were considered separately as the proximal chevron is technically a more difficult procedure than the distal chevron. In these trials, there was no evidence of a significant difference between the osteotomies.

Basile *et al* (2000) found that the chevron osteotomy combined with an Akin osteotomy was more beneficial in correcting the HV angle than the comparison of an Akin osteotomy plus distal soft tissue reconstruction. However, the difference was not significant.

Surgeon's adaptation

None of the three trials comparing a surgeon's adaptation with an original operation showed benefit of the adaptation. As, again, these were small trials with flawed method, it is unlikely that they alone could provide answers. Many of the 100 operations for hallux valgus have been created through small adaptations to an original operation. Surgeons, in fact, commonly use only a few basic types of HAV operation. Given this, future research effort may be best deployed on comparisons of core operations that are used for similar patients or foot type, rather than adaptations by individual surgeons.

New method of fixation versus original method of fixation

Only two of the three trials comparing different fixation techniques provided suitable data for analysis. Calder *et al* (1999) and Prior *et al* (1997) both found no detriment to using new techniques in any of the outcomes measured in this review. Calder undertook a small trial of poor quality comparing screw fixation to suture fixation of cut bone ends. The authors report how the screw fixation allowed early weightbearing to occur without problems which would have obvious benefits to the participants in allowing them to return to work and social activities. Although the number of complications in each group were small, the authors noted that around 15 per cent of cases fixed by screws, had to have the screws removed under local anaesthetic by 6 months due to pain at the fixation site. The second trial (Prior *et al* 1997) was of good quality and considered many different outcomes. The authors state that the absorbable pin would have benefits over the other fixation methods such as sutures, by providing greater stability to the cut bone ends, therefore reducing the chance of displacement deformities and since the pins are absorbable, they have the benefit over K-wires which have to be removed after 6 weeks - a procedure which can be uncomfortable and the patients fear. A decrease in bone density along the pin tract is known to be a complication with absorbable pins, but no difference in density of the metatarsal head was seen in this study.

Postoperative rehabilitation

The evidence available from the three trials was again very limited with all trials considering different aspects of rehabilitation. A small trial of just 39 participants showed some evidence of improvement in joint range of motion after 3 months and earlier recovery when continuous passive motion was used in conjunction with physiotherapy after an Austin procedure (distal osteotomy). As well as the small size of the trial, and its limitations in method, its generalisability is dubious since physiotherapy is not in universal use. The benefit of physiotherapy alone has not been tested. The long-term benefits of the continuous passive motion have not been tested. There appears to be no detriment in encouraging the patient to weightbear at an early stage after arthrodesis. This result is consistent with the practice that is already undertaken by many surgeons, although the start of weightbearing will often depend upon the type of fixation used in the surgery. There appears to be no detriment to using a crepe bandage instead of a plaster slipper after surgery. The crepe bandage would be considered to be less protective than a plaster cast, but both studies found few cases of non-union in 47 patients. The plaster has the disadvantage of making observation of the foot more difficult so that wound infection is less easily observed and the plaster limits mobility and can rub on the patients foot increasing the risk of new wounds. The authors comment of the cost benefit of using crepe bandage.

Outcome assessment

The assessment of outcome was hampered by the variety and quality of the outcomes recorded in the 21 trials. The HV angle was the most frequently used outcome. In all surgical trials, this measurement was made radiographically. However, radiographic measurement of HV and IM angles has been proven to have poor reproducibility of the X-ray beam angle, foot placement and choice of bony landmarks all influencing the inter and intra-repeatability (Laporta 1974). The change in HV and IM angles also may be inaccurate since many factors can change during the three-year follow up that will alter the measured angle. Strict standardised procedures would have to be adhered to to ensure an accurate assessment of the difference between pre-operative and three-year measurements.

Several of the trials reported pain on a 0-100 visual analogue scale whilst others recorded pain in simple terms of improved, same or worsened pain. Whilst the measurement of pain is recognised to be difficult, and many assessment scales are available, this measure is too vague in the context of this review. For instance, it was unclear whether the pain was within the joint, or was a measure of overall foot pain due to other problems, such as the development of transfer lesions which are seen more commonly with arthrodesis and Keller's arthroplasty. This lack of detail means that it is impossible to account for the high dissatisfaction levels that were apparent, despite potential improvements in the two main outcomes of HV angle and pain.

A few trials used a score combining outcomes such as pain, satisfaction, range of movement in the assessment score developed by the American Orthopaedic Foot and Ankle Society (AOFAS) assessment criteria. Other scoring systems are available and were used occasionally such as the Foot Function Index and the Mayo Forefoot Score (Kataoka 1994). The AOFAS provides a comprehensive assessment and includes both objective and subjective criteria, but a scheme that includes outcomes that are important to the patient has yet to be developed. As with many of the scoring systems, the AOFAS has not been fully validated (SooHoo et al., 2003). A recent outcome score, the Foot Health Status Questionnaire (FHSQ), has been validated and was specifically designed for foot surgery and so may be more appropriate for future trials (Bennett et al., 1998). A study on the factors related to patient satisfaction following HAV treatment is warranted. Such a study could investigate the seeming contradiction where improvement in toe position and reduction in pain do not appear to relate directly with patient satisfaction. Other outcomes that are important to the patient may include improved mobility and footwear requirements. Trials recording footwear requirements focused on simple measures such as whether the patient could wear normal shoes or required specialist footwear. However, footwear requirements may be more subtle, such as being required to wear only one particular heel height if the toe is fused at a certain angle. Patients may also have preconceived ideas regarding the results of surgery that are not realistic. If this is so, it is more likely that they will be dissatisfied with the outcome. This emphasises the importance of addressing such ideas prior to surgery.

Only one study appeared to ask the patients whether they were better, the same or worse than one year previously. Although perhaps not providing sufficient detail for a treatment provider, information on such an outcome would be instantly more meaningful for a patient when deciding whether to undergo a particular treatment.

As well as subjective measures (data reported by the patient), other objective measures (information measured by the practitioner directly from the patient) such as foot loading and gait analysis can be useful. Although these outcomes were used in a few of the trials, the data were not suitable for analysis. Moreover, the Harris and Beath mat used to measure pressure, is nowadays considered a crude method. Improved techniques are available for the measurement of changes in pressure and loading across the foot, the reduction in secondary skin pathologies (corns and callous) and changes in gait patterns. Currently scoring systems, such as the AOFAS, do not include pressure measurement or detailed gait information.

From the pragmatic viewpoint of conducting trials and assessing recovery from surgery, we set a follow-up of one year as being "optimal". However, with hindsight, given the progressive nature of HAV, the one-year or even three-year follow-up, deployed in five of the trials, were insufficient to assess the effects of conservative or surgical interventions. Furthermore, conservative therapies which are designed to modify soft tissue structure and indirectly to produce bony adaptation, may be required for several years to be effective. The influence of wearing sensible shoes has not been evaluated. As well as the potential deterioration in the long term, longer term consequences of surgical correction such as increased problems related to walking on a foot that has undergone bone shortening procedures or where transfer lesions develop, need to be assessed.

Trial Quality

The method quality of the trials was generally poor. Torkki 2001 scored good marks in all areas of the quality assessment except for subject blinding, this being particularly difficult in surgical trials. In the other trials only Resch 1994 reported an adequate method of allocation concealment. In general, the selection of outcome measures was clinically appropriate and the duration of surveillance adequate, however blinding of assessors was attempted in only a few trials. It is recognised that blinding of patients in conservative treatments may be almost impossible and may well be difficult in surgical trials; it may however be possible to blind the assessor for many trials. Again, the surgical trial will be difficult as the techniques may be obvious on X-ray, but the conservative treatments and rehabilitation techniques in future should attempt blinding of the assessor. Many trials also failed to do, or provide data for, intention to treat analysis. The presentation of results by feet rather than by patient in ten trials which were randomised by patient was a particular problem.

It was felt that assessing the quality of the trials may not have reflected the quality of the trials so much as the quality of the reporting of the trials. Many of the studies may have scored higher on their method of allocation concealment and type of randomisation if it had been reported fully.

Addressing the etiology of HAV deformity

In the 21 trials included in this review, the patient groups consisted of 1108 females (91%) and 105 males (9%). Chapter 1 of this thesis found that HAV deformity predominates in females with approximately 25% of females and 12% of males being affected. It would therefore appear that the number of women seeking HAV surgery far exceeds the number of men. Although women may be more concerned about the appearance of their feet, surgeons generally will not undertake surgery for cosmetic reasons alone. Other factors must therefore cause women to seek treatment. Choice of suitable footwear to accommodate the deformity may be one factor. In general, women choose not to wear wide, flat lace-up shoes as frequently as men wear them. Wearing non-accomodative shoes will cause discomfort and may lead to women seeking treatment for their deformity. What is not clear from the literature is whether HAV deformity differs between men and women. Do women seek treatment for HAV more than men because their deformity is more progressive?

When considering the treatments evaluated by randomised controlled trials, none considered the underlying etiology. Many of the surgical treatments addressed the metatarsus primus varus deformity without identifying what had created the deformity initially. Metatarsus primus varus may be congenital or may develop with time, resulting from a force acting on the 1st metatarsal causing adduction. No treatment considered the shape of the metatarsal head as a cause of HAV deformity (chapter 2 and 3) or metatarsus adductus (chapter 2) or the influence of hypermobility (Harris and Beeson, 1998b; Carl et al., 1988). The mechanical causes related to subtalar joint pronation may have been addressed in the conservative trials with orthoses but this is doubtful for the trial by Kilmartin when the 1st ray position was not stabilised and in Torkki's trial did not state what mechanical problems were being addressed.

6.28 **Conclusion**

There is some evidence to suggest that surgical treatment is superior to conservative treatment in the treatment of hallux valgus deformity. From this review, no good evidence was found that conservative treatments, involving splinting or orthoses, prevent the progression of hallux valgus deformity. Conservative treatments appear to be of little use in the control of deformity or improvement in pain or function in the long term although only two forms of conservative treatment have been tested in RCTs. One good study comparing surgical correction of hallux valgus with conservative treatment or no treatment found in favour of the surgical treatment. Only a small proportion of available surgical treatments have been evaluated with randomised controlled trials. In the trials reported, there was no evidence that any one type of surgical procedure was superior to another across a range of outcomes. New methods of fixation being introduced into surgical practice do not appear detrimental to traditional methods, although benefits to the patient in terms of early return to activities need to be demonstrated.

Of the 21 trials included so far in this review, most were small (under 100 participants) and only the most recent trials showed improved methodology. Non-English language trials and older trials tended to be methodologically flawed, particularly in respect to masking of allocation concealment and outcome assessment as well as intention-to-treat analysis. Some of the findings were plausible and consistent with our views of current practice, but none of the evidence was sufficient to confirm current practice. Though a reasonable attempt to assess outcome was made by most of the trials, there is room for substantial improvement both in terms of greater emphasis on patient derived outcome measures and longer duration of follow-up.

Evidence from randomised studies for the effectiveness of treatments for hallux valgus is limited by a paucity of good quality, large sample trials. Patients and health professionals would benefit from information from randomised trials comparing all commonly used treatments. Good quality trial design and conduct are required. Validated patient-derived outcome measures should be included. Follow up should be for a minimum of three years. Randomised trials should also be conducted for those categories of hallux valgus in which a realistic management choice exists between operative and non-operative management (for example, operation versus the lifetime provision of individually manufactured footwear in older individuals).

6.3 Publications

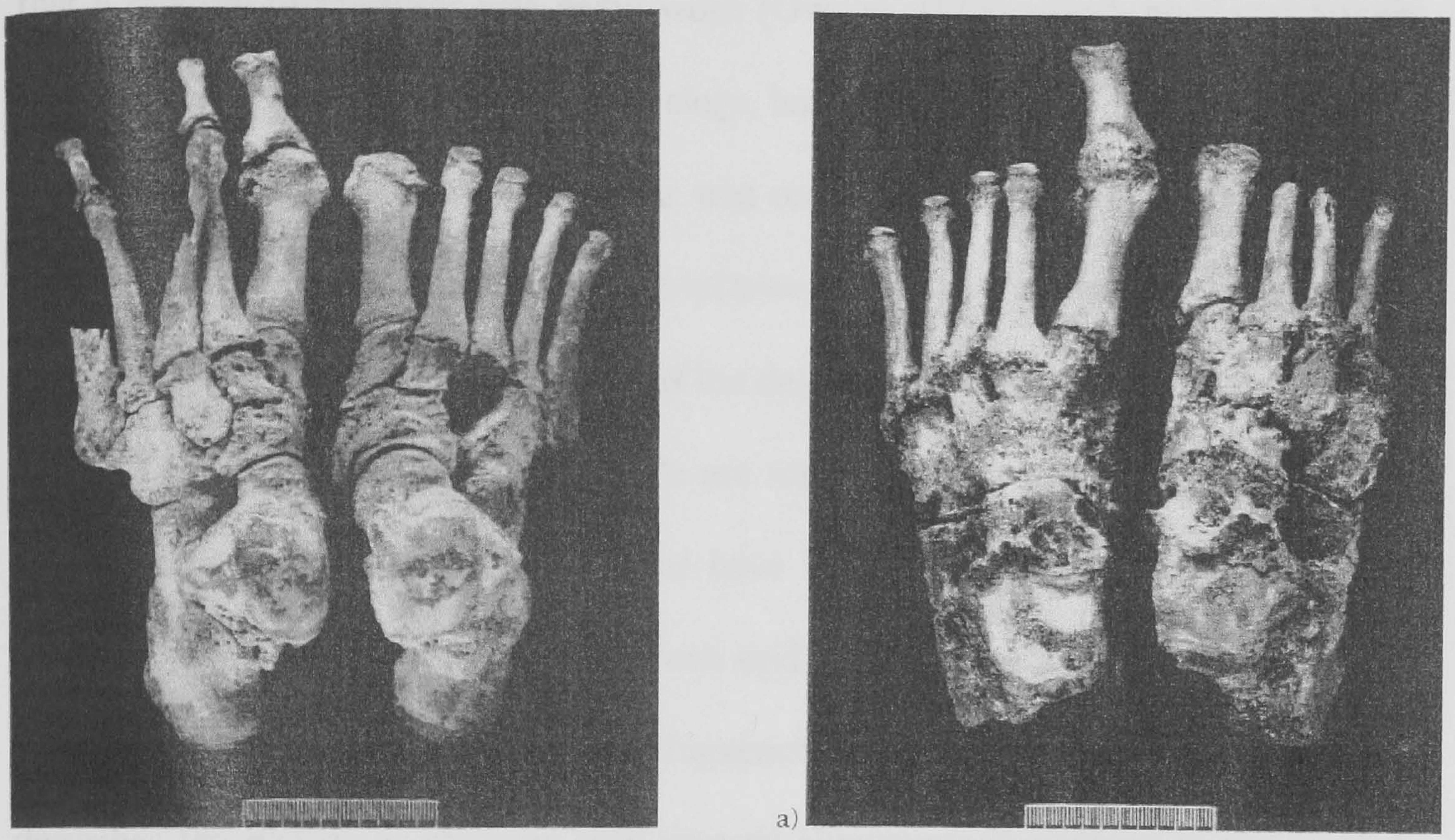
This review has been accepted for publication in the next issue of the Cochrane Database of Systematic Reviews (November 2003), Cochrane Library (2003/4).

CHAPTER 7 DISCUSSION

This study has reviewed the literature on the prevalence of HAV deformity and found that although the condition does occur in men, it predominantly affects women. The predominance in the female foot occurs at all ages, being demonstrated in children as young as those attending primary school (6-11 years). Past studies on the etiology of HAV deformity have considered many different areas such as the shape of the foot bones, the muscular attachments around the metatarsophalangeal joint and foot function. Very few studies have looked for differences in male and female feet with respect to HAV deformity. Studies comparing the male and female foot may highlight the anatomical or functional etiology better than studies comparing groups with and without the deformity. When comparing groups with and without HAV deformity it is difficult to identify whether the HAV is a cause or a result of the factor identified. An example of this was given in chapter 2 when the shape of the metatarsal head was investigated by Brahm (1988). Brahm felt that increased roundness of the metatarsal was an etiological factor in HAV deformity, however the shape of the metatarsal head may have been caused by the HAV deformity through remodelling of the joint surface. The change in position of the proximal phalanx would alter the forces acting through the metatarsal head and thus cause bone resorption and re-shaping in response to the new direction of the forces. Brahm felt that if the rounding of the metatarsal head occurred in response to the HAV deformity then osteoarthritic changes would have been seen. If HAV deformity was responsible for changing the shape of the metatarsal head, then it would be expected to cause similar changes in males and females and the association between HAV and the functional angle would have been the same for each gender if no interaction with other factors occurred. The study undertaken in chapter 2 found that the metatarsal head was generally more rounded in women, yet the association between HAV and the functional angle was less strong in women compared to men. Unfortunately in the study, the women had a greater mean HAV deformity which may have caused a difference in force on the metatarsal head and thus accounted for the mean difference in shape described. The study could have been improved by looking at males and females that were matched for the degree of the joint deformity.

The likelihood that several factors are involved in the development of HAV deformity would account for the differences in the associations with males and females, as measured in chapter 2. One potential etiological factor with an obvious difference between the sexes is footwear. Throughout the literature on HAV deformity, the influence of footwear has been continually questioned. It was hoped that the review of the studies on HAV in childhood (chapter 1) would clarify the influence of footwear since it would be expected that the style of shoes worn by young boys and girls were similar, unlike those worn by adult men and women. However, there was a lack of detail in the studies regarding the style of shoes worn or how the fit was assessed and thus the influence of footwear was unclear. There has been no study undertaken using a reliable measuring device such as the clinical goniometer to measure the degree of deformity and standardising the assessment of the fit and style of the shoes worn. Such a study would have to be undertaken prospectively to follow a group of children over several years to monitor the footwear worn and the development of HAV deformity. A prospective study would also be useful to confirm whether the shape of the metatarsal head changes as the deformity develops. Any prospective study on the development of foot deformity would require investigation over a long time period and require a large number of subjects, perhaps with controlled footwear conditions and would therefore be difficult to undertake. In adults, a retrospective study on the influence of footwear is being attempted with the use of a "Life-Grid" whereby the recall of past footwear worn is aided through the use of list of notable events in history, fashion and the person's family life. However, the pilot studies have suggested that many women cannot accurately judge the heel height of a shoe, most often underestimating it, despite having good recall of when they wore a particular style (Dawson et al., 2003).

With regard to the influence of environmental conditions, such as footwear or lifestyle, on the shape of the metatarsal head, it was interesting to note that there was good agreement between the results of chapter 3 and those of chapter 2, despite the potential differences in the populations studied. The 3-D study in chapter 3 also found that the metatarsal head was more rounded in women. Because the skeletons examined were disarticulated, it was not possible to measure the HA angle and thus the association between the shape of the metatarsal head and the HAV deformity could not be tested. However, several other differences were noted in other foot bones of the male and female skeletons that, when considered together, suggested that the first metatarsal was more adducted in women and thus predisposed women to HAV deformity. Could the differences found in chapter 3 be linked to footwear or environmental differences between the males and females in the population studied? To answer this, more information on the life of the study population was required. The skeletons were taken from the British collection at the National History Museum. They were from the Spitalfields Collection known to be Huguenots living between 1647 and 1847. Given that the earliest references to the treatment of HAV deformity were made in the 19th century when surgical treatments and mechanical devices to correct the deformity were being developed (Dagnall 1994) it is certainly possible that some of this population would have had HAV deformity. In two skeletons, one from a 53 year old man and the other from a man of unknown age, where the bones were articulated due to a degenerative joint condition, a moderate degree of hallux valgus was seen (see figure 102).



a)

Figure 102 showing two male skeletons with HAV probably associated with an underlying connective tissue disease.

The prevalence of the HAV deformity in the 17th and 18th century is unknown but comparisons, in terms of lifestyle and footwear, can be made to the present day population.

It is reported 40,000-50,000 Huguenots escaped to England from France. At this time, some Huguenots already lived in this country, with the first Huguenot church being founded in 1550. Within such a large population, both rich and poor people would exist. The majority of reports that are available describe the wealthy families and individuals such as Sir Richard Houblon (1672-1724), a Huguenot who became the director of the Bank of England in 1713 (Murdock, 1985). The development of the French Protestant Hospital in the east end of London, where the poor were given aid, money, clothes and healthcare, shows that there were many poor Huguenots also in the area. The portraits and illustrations of the Huguenots in the 1700-1800s shows that a mixture of footwear was being worn (Gwynn, 1985). Both male and female working class people would often wear clogs, but these were generally confined to the very poor or where protective footwear was required as part of the job otherwise a flat, laced boot was commonly worn (McDowell, 1989) However, the wealthy were very much following the fashion shoe of the day. In the picture "Noon" by William Hogarth (1738), two fashionable people are seen passing a group of poorer people leaving church (see figure 103). There have been different interpretations of this picture. The fashionable couple have been said to be "native Londoners" mimicking French fashion in front of the poor Huguenots (Murdoch, 1985) whilst Molleson describes the picture as showing well-dressed Huguenots in contrast to the English rabble. Whichever version is correct, the picture shows the fashionable pointed, buckle footwear for men and women and whilst not visible in the picture, it is most likely that poorer classes were wearing the traditional flat, laced boot.

Figure 103. "Noon" by William Hogarth (1738)

Image removed due to third party copyright

For men, boots were in fashion from the late 1600s until the early 1900s (Bordoli, 1958) although only shoes are seen to be worn in the Huguenot illustrations available (see figure 104).

Image removed due to third party copyright

Figure 104. Cartoon of a Huguenot doctor in traditional heeled shoes.

A popular style in 1688 was the high stiff Jack boot which had a small heel, slightly pointed toe-box and a wide upper (see figure 105). In the 1700s, the boots were refined so that they fitted closely to the wearer's calf, such as the Hessian boot (figure 106). Again, the toe-box was pointed.

Image removed due to third party copyright

Figure 105. The High stiff Jack boot

Image removed due to third party copyright

Figure 106. The Hessian with turn-over top

The most frequently worn men's shoe shown in illustrations of Huguenots was similar to the ladies shoe shown in figure 107 (5) having a higher heel than is fashionable nowadays, being slightly pointed at the toe-box and having a decorative buckle.

The fashionable lady's shoes also maintained a similar style from the 1600-1800s. The "pantouffles" was a slipper frequently worn and which was developed in the 1700s by the adornment of bows, laces and ornamental fastenings. Thin soles, high heels and embroidered silk uppers were seen in the early 1700s but by the late 1700s, most ladies shoes became almost flat heeled. Figure 107 shows the typical shoe styles of that time. Of note, there was little difference between left and right shoes so the shoes could be worn on either foot ("straights") and the pointed toe-box was similar for men and women.

Figure 107. Ladies shoe 1778, 2. Ladies shoe 1789, 3. Ladies shoe 1795, 4. Man's dress boot 1872, 5. Buckle shoe, 18th century.

Image removed due to third party copyright

Ladies dress shoes would have had pattens added for walking in the streets to lift them clear of the mud and street rubbish. In the Huguenot portraits available it is difficult to see the ladies shoes clearly as the dress length was such that little of the shoe is visible. When dressed for portraits, the female shoe was found to be more pointed than the male shoe, but heel heights were very similar between the sexes.

Because the excavation of the Spitalfields site was so carefully undertaken, much is known about the individuals taken from the crypt. The fact that the individuals were buried in the crypt, many in family plots or decorative coffins, shows that the population of the Spitalfields collection was generally wealthy. Some remains were found with gold wedding rings or had gold fillings and porcelain dentures (Reeve and Adam, 1993). Molleson stated that *"their socio-economic status would have made it likely that they would have followed the fashions relating to diet"* and from this we can also infer fashion in clothes and shoes. Molleson (1993) lists ten causes of skeletal variation: (1) Inheritance (2). Environment (3). Nutrition (4). Age (5). Habit (6). Occupation (7). Disease (8). Death (9). Decay and (10). Fossilization. In the population measured, differences between males and females would mainly stem from the environment (ie. footwear, work) or perhaps inheritance – the genetically determined shape of the female or male bones. The work environment probably did not play a role in the differences between the bones seen. In this wealthy group, the women were unlikely to have had an occupation and the men would have had managerial or professional roles. An earlier study in this population found no association between osteoathritis in a joint and occupation of the individual (Molleson 1993). Unlike the contemporary population where osteoarthritis is more prevalent in women, in the Spitalfields collection the men showed more signs of OA. Illness also did not appear to differ between males and females and only one death was noted to be foot related with the subject dying from "mortification in the feet".

From the information available about the population of Huguenots used in this study, it is difficult to ascertain with any degree of certainty, whether the differences found between the male and female foot bones would be due to re-shaping of bones secondary to HAV deformity or whether the differences preceded the onset of HAV deformity. It is probable that HAV deformity existed in this population but there is little reason to expect it to be more prevalent in women more than men given the lifestyle and fashion of this wealthy group.

Whilst the findings of chapter 2 suggested an association between the shape of the bone metatarsal head and the HA angle, and was described in terms of greater abduction of the proximal phalanx occurring on a more rounded metatarsal head, the development of HAV deformity is believed to be initiated by the development of the metatarsus primus varus (MPV) deformity. The literature review in chapter 3 charted the evolutionary reduction in the angle of adduction of the first metatarsal from apes through to homo sapiens using the fossil record. No evidence of a difference in the process of evolution was found between males and female feet. The results in chapter 3 found several differences in male and female bones, that together could account for a greater adducted 1st metatarsal position in females and thus an underlying predisposition to MPV deformity. The differences had never previously been recorded in the literature. Because the bones were disarticulated it would be important to repeat the study in articulated cadavers and test whether the assumptions made regarding the movements of the bones in respect to different shaped joint surfaces, were indeed correct. The study hypothesised that the morphology of the female foot was different to the male foot and that the difference in the size of the foot bones and shape of the articular facets would indicate that the feet are structurally different and would therefore function differently. This hypothesis was not rejected. The shape of the joint surfaces of the bones of the medial column of the foot described in chapter 3 suggested that a greater degree of adduction of the 1st metatarsal (metatarsus primus varus) in the female was present which would predispose females to the development of hallux abductovalgus deformity. Whether these changes had occurred due to a difference in the rate of evolution between males and females was not identifiable from the available literature or data.

The study also hypothesised that since females are known to be more flexible than males, increased mobility would be reflected in the lower limb and foot of females. This increased flexibility would exacerbate an underlying preponderance to HAV deformity such that an association would be seen with increasing flexibility and increased HAV deformity. It was also hypothesised that hypermobility in the lower limb or an underlying difference in the bone structure of the foot between males and females would influence the pressure patterns under the foot. Chapter 4 developed a new measuring system to identify lower limb hypermobility since the gold standard method of assessment only included the knee joint movement, with all other joints tested being in the upper limbs or trunk. Using the new scoring system, it was found that females were indeed more flexible than males – and this was found in a much younger age group than many of the previous studies undertaken. However, an association with HAV deformity was not seen in the general population but only in children pre-diagnosed with hypermobility and the number of children in this group was small. It was felt that the lack of a relationship in the population of school children measured may have been influenced by the low incidence of HAV deformity in the age group studied and thus a larger sample size would be required to identify potential associations. It was also considered that the children who remain hypermobile for life would develop the deformity, rather than those that lose their hypermobility naturally with increasing age. That a relationship between HAV and hypermobility existed in the "hypermobile" group was interesting considering that many of these children did not met the Beighton criteria for hypermobility. It was unclear what the specialist had identified that made the diagnosis. It may have been other factors such as laxity in the skin, easy bruising or laxity rather than range of joint motion that was seen. Children with these factors plus a tendency towards flexible joints may have true hypermobility, these children then having a predisposition to HAV deformity. The study could be repeated in one or two ways. Either a comparison could be made between age and sex matched children with and without HAV deformity or a cohort of children could be followed over several years. Given that only 2-3 children per 100 are likely to develop HAV deformity at 10 years old, the study would have to include a large number of children.

The study on pressure patterns and hypermobility in chapter 5 did not identify any trends related to the degree of flexibility of the child but did show some differences between the weightbearing pressures in males and females. A "first step" method was used to record the pressure measurements and this may not represent the pressure patterns occurring in continuous walking. Therefore further studies would be indicated to test whether the first step is different from a mid-gait footstep when the foot is not accelerating or decelerating the body. A barefoot method, such as the one used in chapter 5, does not represent the interaction between the shoe and the foot and since people are generally shod, it would be appropriate to repeat the study using an insole-pressure measurement system. The influence of the differences in forces acting on the hallux in males and females could then be investigated. The study did not identify differences between the hypermobile and non-hypermobile foot. Since there are many gait variables that can be measured when analysing foot pressure data, it may be that the variables chosen in this study, which were based upon other pressure studies, were not suitable or not sensitive enough. A study to investigate more suitable gait variables could also be undertaken.

Finally, the treatments used to correct HAV deformity were reviewed in order to compare the most effective treatments with the factors identified in this thesis. Randomised controlled trials on HAV deformity were selected since they represent the best trial design for identifying effectiveness of treatment. The systematic review found that no surgical procedure was more effective than any other. This may have been due to the lack of good quality trials of good sample size. Only those surgical treatments correcting MPV deformity addressed a specific etiological factor. The underlying reason for the MPV deformity was not considered. Because the follow up of cases was relatively short (3 years), it is not known how many cases of HAV reoccurred due to not addressing the underlying etiological factors. The conservative treatments made some attempts to address underlying etiological factors with studies on orthoses trying to correct the mechanical alignment of the foot although it was unclear from the literature, if the exact mechanical problem was identified and this may be why the conservative treatments did not prove successful.

Proportionally far more women that men sought treatment for their HAV deformity. It is unclear from the studies why this should be. One would suspect that it may be a cosmetic desire or footwear problem that leads women to seek treatment more than men. However, this is speculation. It may be that, if the underlying structure of a woman's foot is different to a man's, then the HAV that develops is also different, being perhaps more unstable and thus more symptomatic in women. A comparison of the long-term outcomes in men and women following HAV surgery would also be interesting regarding the rate of reoccurrence of the deformity. It is hoped that the systematic review will encourage more research into HAV treatments, with evaluation through RCTs and using longer follow-up times.

This thesis has presented evidence that there are some differences in the structure and function of male and female feet. Such differences may predispose the female to hallux abductovalgus deformity. The underlying shape of the bones in the female foot are such that they may predispose the female to HAV deformity. Although the shape of the bones cannot be altered, it may be possible to identify those who are at risk. Such people could then make the choice as to whether they address some of the other factors that may add to the deformity, such as footwear or abnormal foot biomechanics, although at this stage the influence of these factors remains unknown.

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GLOSSARY

AOFAS	American Orthopaedic Foot and Ankle Society
COP	Centre of Pressure
HA	Hallux abductus
HAV	Hallux abductovalgus
HC-CENT	Heel contact to central metatarsal loading
HC-TO	Heel contact to toe off
HV	Hallux valgus
ICC	Interclass correlation coefficient
IM	Intermetatarsal
LFH	London Foot Hospital
LLAS	Lower limb assessment score
JIA	Juvenile idiopathic arthritis
MA	Metatarsus adductus
MD	Mean difference
MPV	Metatarsus primus varus
MTPJ	Metatarsophalangeal joint
NPV	Negative predictive value
OA	Osteoarthritis
OR	Odds ratio
PASA	Proximal articular set angle
PPV	Positive predictive value
RCT	Randomised controlled trial
ROC	Receiver operating characteristic

APPENDIX I

MALE AND FEMALE BONE SHAPE:

- **A RADIOGRAPHIC STUDY OF THE FOREFOOT**
  - **REPEATABILITY STUDIES**

1. To test the influence of the X-ray beam angle on the hallux abductus angle

The radiographs used for the main study were all selected from the collection held at the London Foot Hospital. These had been taken at the Royal National Orthopaedic Hospital (RNOH) using the standard technique of placing the beam at an angle of 15 degrees to the navicular (-15°), at a distance of 100cm from the foot. Since the placement of the beam was arbitrary, the influence of different beam angles on the HA angle was investigated.

Method:

One foot cadaver was obtained from the Department of Anatomy, UCL. This was X-rayed at the RHOH. The foot was clamped in a weightbearing position to prevent movement. The X-ray tube was placed 100cm from the foot. A digital spirit level was fixed to the top of the X-ray tube. The tube was tilted through seven different beam angles:: -15°, -10°, -5°, 0°, 5°, 10° and 15° resulting in seven radiographs.

The hallux abductus angle was measured 5 times for each beam angle. The order of measurement was random.

Results:

Each radiograph was measured five times (see table 1).

Table 1. Results of HA angle for one cadaver with various X-ray beam angles

Beam Angle		15°	10°	5°	0°	-5°	-10°	-15°
Repeats	1	19	17	17	20	18	20	19
	2	19	18	17	18	18	18	17
	3	20	19	18	18	19	17	17
	4	20	19	20	18	18	17	17
	5	18	20	19	19	16	17	15

The influence of beam angle on the HA angle was tested using a two factor ANOVA. The analysis was divided into positive and negative beam angles. It was felt that since the beam angle should be directed -15° to the navicular, it would be unlikely that a radiographer would select a positive angle, but the selected negative angle may vary.

Initially the positive beam angles were compared (0°,5°,10°,15°). No significant difference between HA angles was found (p=0.63) (see table 2).

Table 2. Two factor ANOVA for HA angle at beam angles 0-15 degrees.

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Rows	493.6667	19	25.98246	0.860471	0.628194	1.867331
Columns	52087.23	2	26043.62	862.4967	2.17E-32	3.244821
Error	1147.433	38	30.19561			
Total	53728.33	59				

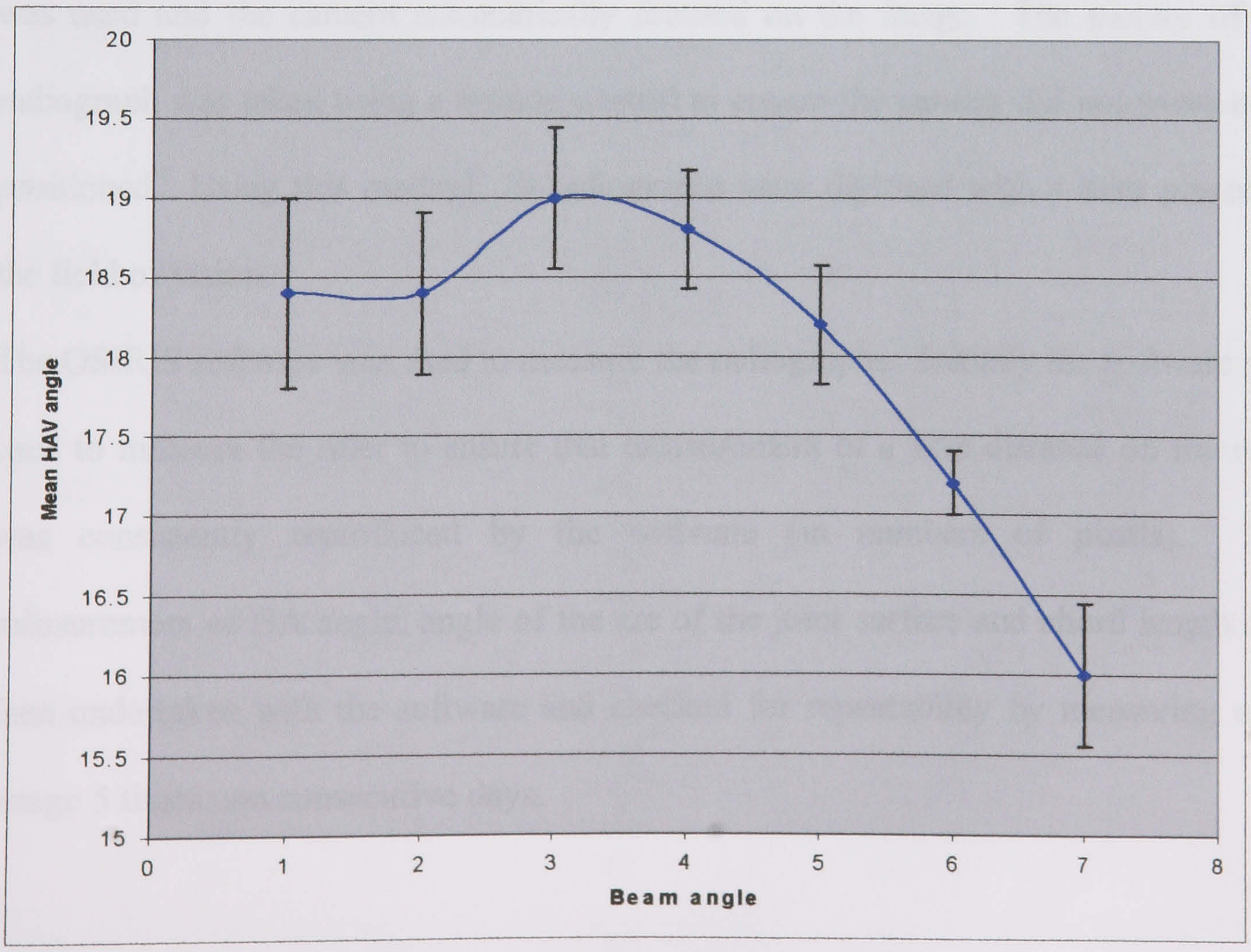
The negative angles were then compared (0°, -5°, -10°, -15°). No significant difference was found between the HA angles (p=0.996) (see table 3)

Table 3. Two factor ANOVA for HA angle at beam angles 0- -15 degrees.

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Rows	231.5167	19	12.18509	0.305909	0.996224	1.867331
Columns	54091.03	2	27045.52	678.9819	1.83E-30	3.244821
Error	1513.633	38	39.83246			
Total	55836.18	59				

Figure 1 demonstrates how the HA angle shows little difference for the angle 0 to –15 degrees (beam angles 1-4) but greater variability for angle 0 to 15 degrees (beam angles 4-7).

Figure 1. Graph demonstrating variability in HA angles for beam angle 15° to -15°



C

Conclusion:

Because there was no significant difference between X-ray beam angle and HA angle, it was considered acceptable to select radiographs for the main study from the collection at the London Foot Hospital.

2. To test the repeatability of the digitised image

Method:

Each radiograph was placed illuminated on an X-ray box. The box was placed at 1m from the digital camera. The camera was fixed to the tripod and had a small torch attached to the top alongside a spirit level. Using the camera viewer, the tripod was raised or lowered until the light from the torch was centred on the first metatarsal. The spirit level ensured that the camera was not tilted. The maximum zoom position was used and the camera automatically focused on the image. The picture of the radiograph was taken using a remote control to ensure the camera did not move once positioned. Using this method, 20 radiographs were digitised with a ruler placed in the field of vision.

The OSIRIS software was used to measure the radiographs. Initially the software was used to measure the ruler to ensure that measurement of a 1cm distance on the ruler was consistently reproduced by the software (in numbers of pixals). The measurement of HA angle, angle of the arc of the joint surface and chord length was then undertaken with the software and checked for repeatability by measuring each image 5 times con consecutive days.

Results:

Table 4 shows the raw data collected.

Table 4. Data for 20 radiographs

Patient number		No.of pixals per cm	Chord length (pixs)	angle of arc (degs)	hav angle (degs)
LB6919	Repeat 1	46.8	87	123	7
	2	47	84	122	10
	3	47	82	126	10
	4	47	85	127	9
	5	47	85	120	7
LB6933	Repeat 1	42	75	137	9
	2	41.8	72	141	12
	3	41.8	76	142	9
	4	41..8	72	139	10
	5	42	71	135	10
LB6963	Repeat 1	41.8	74	144	12
	2	42	74	140	10
	3	41.8	71	139	10
	4	41.8	74	140	11
	5	42	77	141	9
LB7036-L	Repeat 1	28.8	47	136	19
	2	29	48	133	19
	3	29	48	134	19
	4	29	48	135	20
	5	29	48	138	21
LB7036-R	Repeat 1	28.8	55	122	10
	2	29	51	130	9
	3	29	49	132	11
	4	29	53	132	11
	5	29	50	126	10
LB7100-L	Repeat 1	32.4	59	114	29
	2	32.6	58	120	31
	3	32.6	55	119	28
	4	32.4	58	115	31
	5	32.8	58	115	29
LB7100-R	Repeat 1	32.4	58	128	20
	2	32.6	58	128	21
	3	32.6	58	128	21
	4	32.4	58	129	19
	5	37.2	58	128	19
LC1669	Repeat 1	37.2	69	133	20
	2	37.4	68	132	20
	3	37.6	67	132	18
	4	37	69	133	20
	5	37.4	67	135	19
LC1697	Repeat 1	38	69	126	22
	2	37.8	66	126	22
	3	38	66	130	21

f

	4	37.8	69	126	23
	5	38	66	130	22
LC1703	Repeat 1	38.2	74	133	15
	2	38.2	71	136	17
	3	38.4	70	133	18
	4	38.2	71	136	16
	5	38	69	131	17
LC1707	Repeat 1	38.8	80	135	13
	2	39.2	81	134	10
	3	39	79	136	12
	4	39	78	138	14
	5	39	76	141	12
LC1715-L	Repeat 1	43	70	127	31
	2	43.2	71	122	31
	3	43.2	70	122	30
	4	43	71	125	28
	5	43	71	126	30
LC1715-R	Repeat 1	43	66	120	38
	2	43.2	61	127	38
	3	43.2	61	125	39
	4	43	62	128	39
	5	43	63	128	35
LC1884	Repeat 1	43.2	68	129	16
	2	42.6	65	124	19
	3	43	66	127	17
	4	43.2	65	123	17
	5	43	63	125	17
LC1887	Repeat 1	43.2	68	127	17
	2	43.2	65	128	18
	3	43.4	66	126	17
	4	44	68	129	18
	5	44	64	126	18
LC1914	Repeat 1	36.6	65	124	32
	2	36.8	66	124	29
	3	36.8	65	126	30
	4	36.8	65	130	29
	5	36.7	65	121	29
LC2037	Repeat 1	44.8	75	130	27
	2	44.8	75	126	26
	3	44.4	74	127	27
	4	44.6	74	127	25
	5	44.5	76	122	28
LC2073	Repeat 1	41	69	126	25
	2	40.8	68	126	26
	3	40.8	70	126	26
	4	41	69	128	26
	5	39.8	69	126	26
LC2080	Repeat 1	40.2	68	133	17
	2	40.2	68	135	16
	3	40.4	70	130	17

F

	4	40.6	70	133	15
	5	40.2	67	135	14
LC2109	Repeat 1	33.8	64	129	21
	2	34	60	124	19
	3	34	62	125	21
	4	33	64	126	20
	5	33	60	125	19

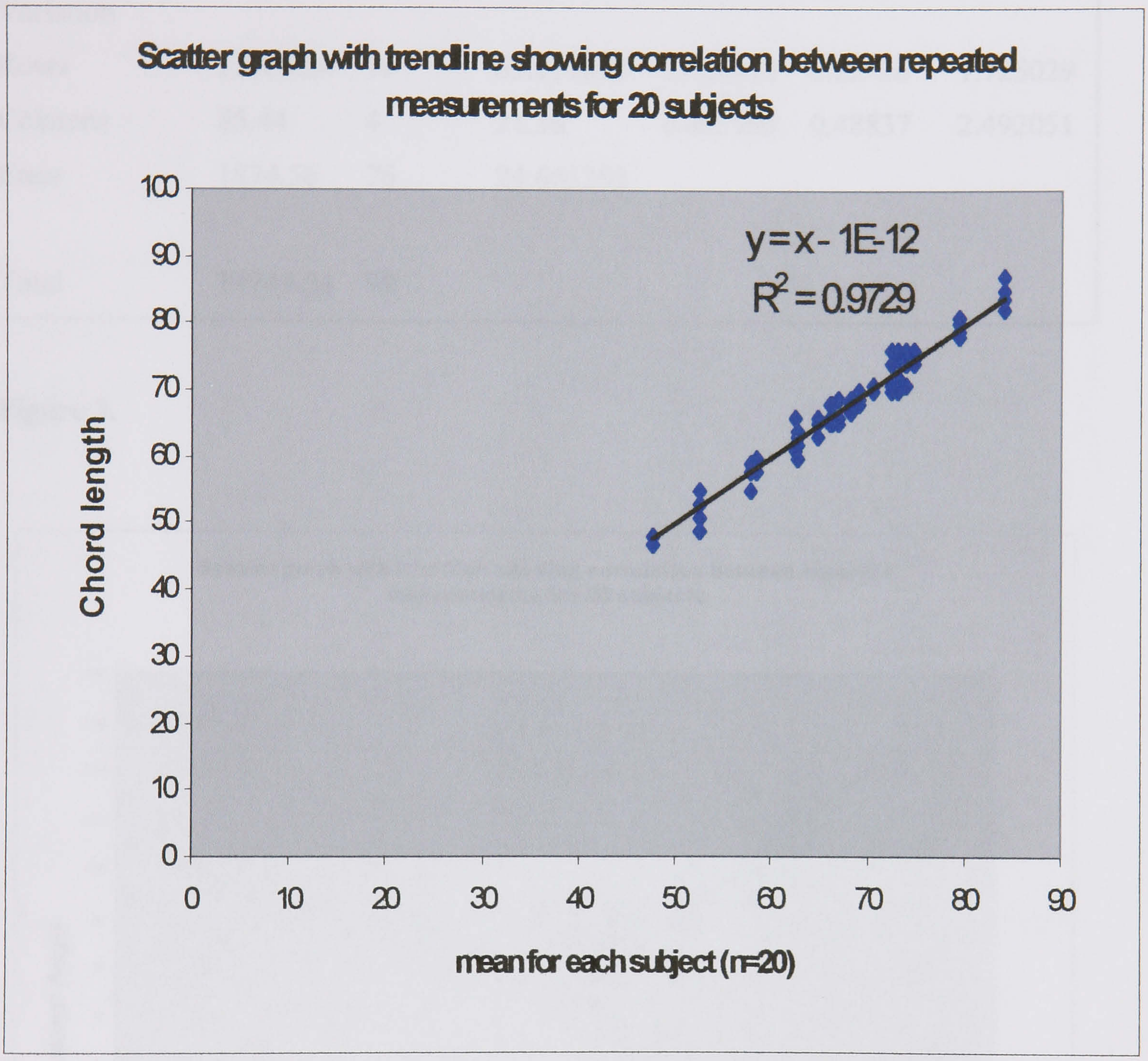
The chord length, angle of arc and HA angle were each tested for repeatability two methods. A two factor ANOVA was applied to test for differences between the individual patients and for differences between the repeats. The measurement was compared to the mean of the 5 repeats, for each patient. The correlation between the measurement and it's mean was tested.

There was no significant difference in the measurements of chord length between each repeat ($p<0.001$) but there was a difference between each subject ($p=0.32$)(see table 4) when tested with a two factor ANOVA. The scatter graph showed good correlation between the measurement and the mean of the repeats ($R^2=0.973$) (see figure 2)

Table 4. Two factor ANOVA for chord length.

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Rows	7452.96	19	392.2611	226.293	6.74E-59	1.725029
Columns	8.26	4	2.065	1.11286	0.321528	2.492051
Error	131.74	76	1.733421			
Total	7592.96	99				

Figure 2.

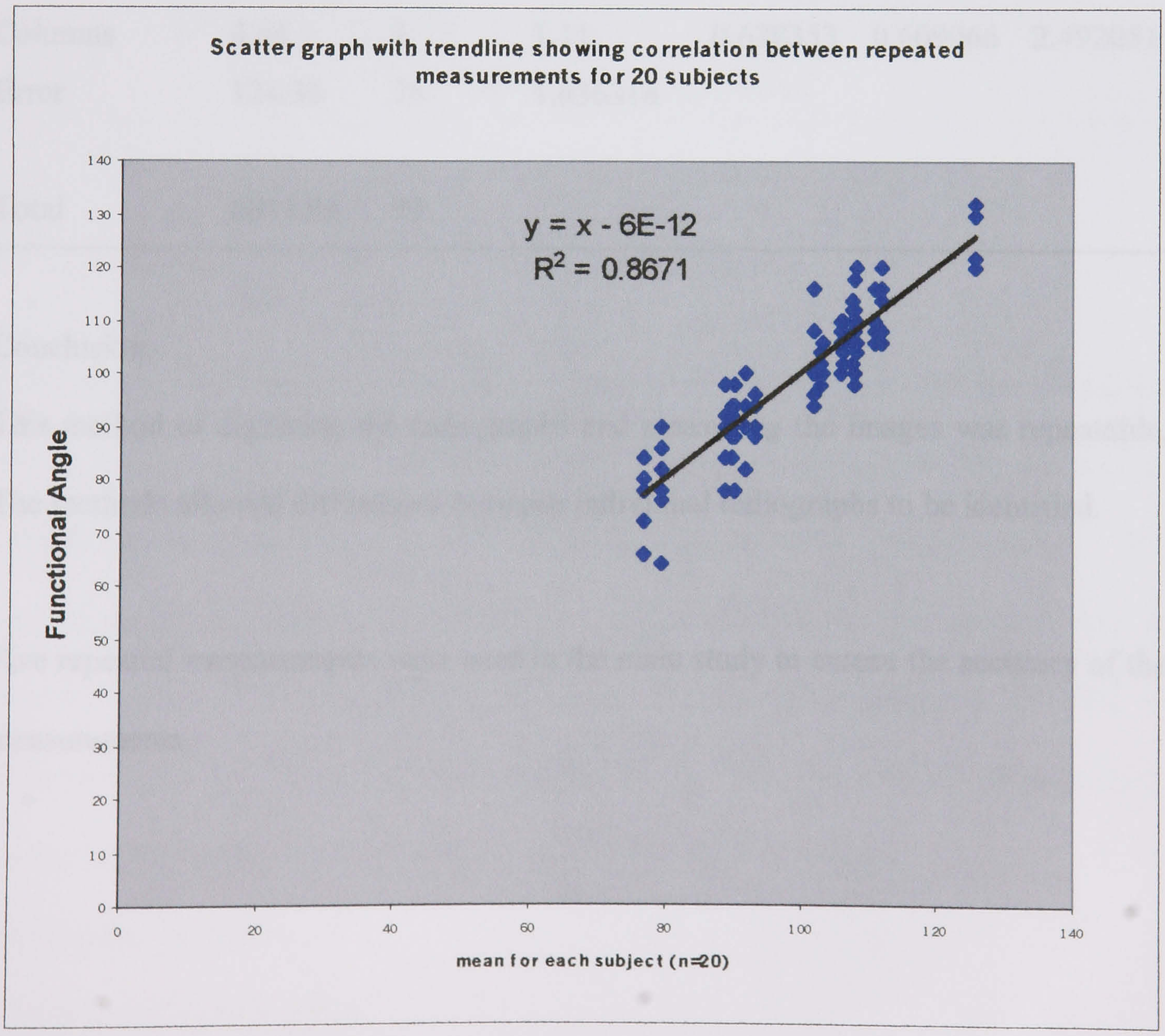


There was no significant difference in the measurements of the angle of the arc between each repeat ($p<0.001$) but there was a difference between each subject ($p=0.48$)(see table 5). The scatter graph showed good correlation between the measurement and the mean of the repeats ($R^2=0.86$) (see figure 3)

Table 5. Two factor ANOVA for angle of arc.

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Rows	12789.24	19	63.117895	27.29012	2.2E-26	1.725029
Columns	85.44	4	21.36	0.865995	0.48837	2.492051
Error	1874.56	76	24.665263			
Total	14749.24	99				

Figure 3.



I

There was no significant difference in the measurements of HA angle between each repeat ($p<0.001$) but there was a difference between each subject ($p=0.61$)(see table 6). The scatter graph showed good correlation between the measurement and the mean of the repeats ($R^2=0.983$) (see figure 4)

Table 6. Two factor ANOVA for chord length.

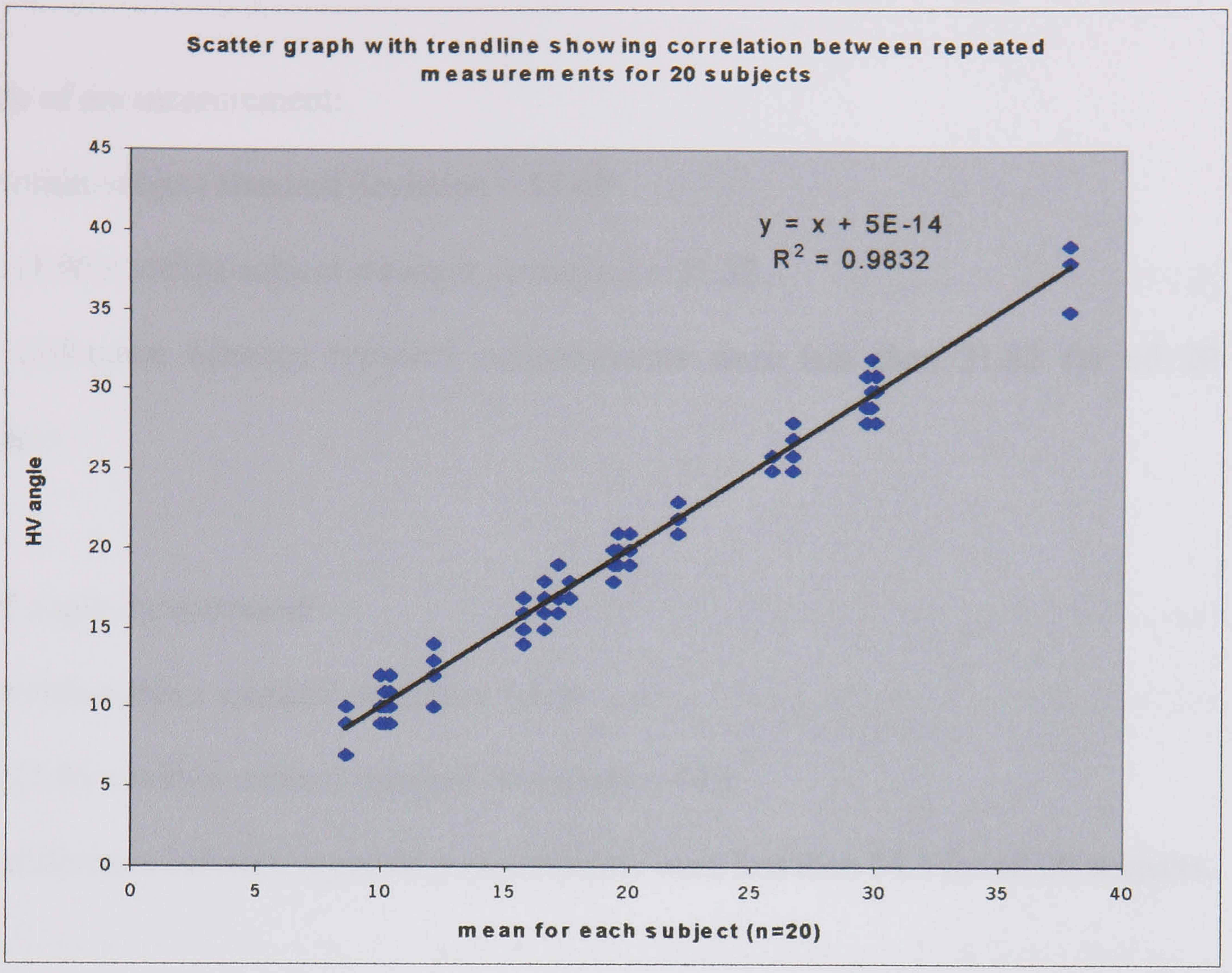
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Rows	5883.04	19	309.6337	189.2261	5.16E-56	1.725029
Columns	4.44	4	1.11	0.678353	0.609066	2.492051
Error	124.36	76	1.636316			
Total	6011.84	99				

Conclusion:

This method of digitising the radiographs and measuring the images was repeatable. The methods allowed differences between individual radiographs to be identified.

Five repeated measurements were used in the main study to ensure the accuracy of the measurements.

Figure 5.



A further way to consider repeatability is suggested by Bland and Altman (Statistics Notes: measurement error, BMJ 312:1654). These Authors suggest that the within-subject standard deviation is calculated for the repeated measurements. The measurement error between a subject's measurement and the true value would be expected to be less than (1.96 x within-subject standard deviation) for 95% of observations. For the difference between the greater and smallest measurement should be less than √2 x (1.96 x within-subject standard deviation).

For the data in table 4:

Chord length measurement:

the within-subject standard deviation = 7.07

√2 x (1.96 x within-subject standard deviation) = 19.6

K

The difference between repeated measurements were less than 19.6 for all 20 subjects.

Angle of arc measurement:

the within-subject standard deviation = 11.49

$\sqrt{2}$ x (1.96 x within-subject standard deviation) = 31.82

The difference between repeated measurements were less than 31.82 for all 20 subjects.

HAV angle measurement:

the within-subject standard deviation = 5.1

$\sqrt{2}$ x (1.96 x within-subject standard deviation) = 14.1

The difference between repeated measurements were less than 14.1 for all 20 subjects.

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APPENDIX II

Publications:

Ferrari J and Malone-Lee J. A study of the relationship of the shape of the metatarsal head and hallux abductovalgus deformity. Foot & Ankle International. 23 (3):236-242, 2002.

Ferrari J and Malone-Lee J. A study of the relationship between the paroximal articular set angle and hallux abductovalgus. J American Podiatric Medical Association. 92(6):331-335, 2002.

Ferrari J and Malone-Lee J. A study of the relationship between Metatarsus Adductus and Hallux abductovalgus. J Foot Surgery. February 2004.

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